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# **Spacelab Science Results Study**

## **Final Report**

### **Executive Summary**

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## Executive Overview

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### Introduction

Beginning with OSTA-1 in November 1981, and ending with Neurolab in March 1998, thirty-six shuttle missions are considered Spacelab missions because they carried various Spacelab components such as the Spacelab module, the pallet, the Instrument Pointing System (IPS), or the MPESS. The experiments carried out during these flights included astrophysics, solar physics, plasma physics, atmospheric science, Earth observations, and a wide range of microgravity experiments in life sciences, biotechnology, materials science, and fluid physics which includes combustion and critical point phenomena. In all, some 764 experiments were conducted by investigators from the United States, Europe, and Japan. These experiments resulted in several thousand papers published in refereed journals, and thousands more in conference proceedings, chapters in books, and other publications. A number of these investigations could be considered as landmark experiments in that they produced results that set the tone for new vistas to be explored, which consequentially added greatly to our body of knowledge of the universe, the planet on which we live, how our bodies and other biological systems function, and the science involved in materials processing.

The purpose of this Spacelab Science Results Study is to document the contributions made in each of the major research areas by giving a brief synopsis of the more significant experiments and an extensive list of the publications that were produced. We have also endeavored to show how these results impacted the existing body of knowledge, where they have spawned new fields, and, if appropriate, where the knowledge they produced has been applied.

The team members that conducted this study and their area of responsibility are:

- Dr. Charles A. Lundquist – Astrophysics
- Dr. Einar Tandberg-Hanssen – Solar Physics
- Dr. James L. Horwitz - Space Plasma Physics
- Dr. Glynn A. Germany – Atmospheric Science
- Dr. James F. Cruise – Earth Observations
- Dr. Robert J. Naumann – Microgravity Sciences (excluding the Life Sciences)
- Dr. Marian L. Lewis – Microgravity Life Sciences

The material used in study came from many sources including the Mission Summary Reports, Mission and/or Investigator Team WEB sites, the International Distributed

Experiments Archives (IDEA, which contains both the NASA Microgravity Research Experiments (MICREX) database and the ESA Microgravity Database), the Compendex\*Web, the Science Citation Index, various survey papers, conference proceedings, and the open literature publications of the Investigators. Unfortunately, the MICREX database, which had been an excellent source of information for microgravity flight experiments, has not been maintained since USML-1, so it is only useful up to that point.

Our initial intent was to assess the scientific impact of these various investigations on the basis of the number of publications generated and the citations they received. It soon became apparent that this would not be a fair assessment for the following reasons:

- Often the total number of publications is dominated by a small number of highly productive teams that flew the same investigation on multiple shuttle flights.
- Time and fiscal restraints for the study did not allow for an exhaustive reference search; thus there is the possibility that key documents to a particular experiment may have been missed.
- Investigators often publish papers using data from multiple Spacelab missions or combine data from Spacelab with other flights. Therefore, it is not possible to ascribe a particular publication to a specific experiment.
- Often the flight data is only a small part of a much larger ground based investigation. It is difficult to determine which of the ground based papers to include.
- Many of the early ESA microgravity investigators chose to present their results at the series of ESA-sponsored conferences instead of the open literature. Therefore, their results, even though important, are not as widely known to the greater scientific community.
- Many of the more exciting results have come on the more recent flights and, therefore, have not had time to collect many citations.

For these reasons, we thought it prudent to simply document the experiments that produced publishable results (even though some were not published in the open literature) by presenting a brief synopsis of their results in context with the state of knowledge in the field (where appropriate) along with the references we have been able to find. The included bibliography is quite extensive, as may be seen in the Table below.

In addition to the 44 references in the Astrophysics section, there are 145 other papers listed in the ASTRO web site reporting observations of specific objects. Also, we understand that there are an additional 538 publications resulting from Spacelab J that were not available to us. Therefore it is safe to say that the Spacelab program has generated in excess of 4200 publications with additional publications expected as the data from MSL-1R and Neurolab finds its way into the open literature. Of these, we estimate that approximately 2400 are published in refereed journals, the remaining appear as chapters in books or in conference proceedings.

Again, time and resources did not permit iteration with the Investigators, as we would have liked to do. So if we misinterpreted a result, we apologize. Invariably, when dealing

with this many experiments in a limited time, we are bound to have left out an important experiment by oversight or because we failed to grasp the significance of the result. Again, we apologize to the Investigators we may have slighted.

**Table 1. Total Publications by Discipline**

<u>Discipline</u>	<u>Total Publications</u>
Astrophysics	44
Solar Physics	28
Space Plasma Physics	140
Atmospheric Sciences	220
Earth Resources	117
Fluid Physics	563
Combustion	118
Materials Science	999
Biotechnology	598
<u>Life Sciences</u>	<u>713</u>
Total Publications	3540

Some of these Spacelab missions were more or less dedicated to specific scientific disciplines, while other carried an eclectic mixture of experiments ranging from astrophysics to the life sciences. However, the experiments can be logically classified into two general categories; those that make use of the Shuttle as an observing platform for external phenomena (including those which use the Shuttle in an interactive mode) and those which use the Shuttle as a microgravity laboratory. Since the resulting study report turned out to be rather unwieldy when all of the references are included, we have broken it down into several volumes by discipline.

This first volume of this Spacelab Science Results study will be devoted to experiments of the first category. The disciplines included are Astrophysics, Solar Physics, Space Plasma Physics, Atmospheric Sciences, and Earth Sciences. Because of the large number of microgravity investigations, Volume II will be devoted to Microgravity Sciences, which includes Fluid Physics, Combustion Science, Materials Science, and Biotechnology, and Volume III will be devoted to Space Life Sciences, which studies the response and adaptability of living organisms to the microgravity environment. In addition, an executive overview of all of the disciplines was prepared (without references) by distilling the inputs from the members of the Science Team.

# Executive Overview

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# Astrophysics

Astronomy and astrophysics are rapidly moving disciplines. Results that were new and important at the time of their release may be superseded by newer results a few years later. The astronomical observations made from the Spacelab missions must be viewed against this general feature of the science. None the less, some of the pioneering work on Spacelab missions have made direct as well as indirect lasting contributions to our current body of knowledge of the Universe.

Spacelab 1 carried three instruments, a Far Ultraviolet Space Telescope (FAUST), a Very Wide Field Camera (VWFC) and a Gas Scintillation Proportional Counter (GSPC). These instruments were hard mounted to the shuttle structure, so that pointing was accomplished by controlling the attitude of the shuttle. Because this first mission expected to demonstrate diverse uses of Spacelab, the instrumentation represented a broad range of disciplines. The two telescope-camera instruments photographed star fields in the far ultraviolet (FAUST) and ultraviolet (VWFC). As might be expected, a principal result was an improved understanding of how shuttle borne cameras of this class can best be employed. Also, the photographed fields provided surveys of ultraviolet characteristics of classes of stars that could be selected for future detailed observation and analysis. The GSPC measured X-ray energy spectra in the range 2-80 keV for Cyg X-3, Cen X-3 and the Perseus cluster of galaxies. The first two are well known X-ray sources for which these measurements provided further information.

The astrophysical instruments on Spacelab 2 probed the universe in the infrared, X-ray, and cosmic radiation spectral regions. For the first of these, a small, helium-cooled infrared telescope (IRT) was mounted on the Spacelab Instrument Pointing System (IPS). It was designed to observe diffuse, extended sources of infrared as well as to augment data on discrete infrared sources, many of which were cataloged earlier by the Infrared Astronomical Satellite (IRAS). An operational question addressed was the suitability of the Shuttle as a carrier for Infrared Telescopes. With respect to this question, the IRT background due to emission of gas from the Shuttle was found to be greater than anticipated. The surveys of the Milky Way Galaxy at 2 and 7 microns were new data, implying that the structure of the Galaxy is broader at these wavelengths than at longer wavelengths.

The objective of the X-ray imaging telescope on Spacelab-2 was to produce images of clusters of galaxies, particularly, and also other extended X-ray sources. A puzzle was the source of the hard X-rays coming from the direction of clusters of galaxies. Hot gas between the galaxies of the cluster was one hypothesis. From spectrally resolved images of the Virgo cluster, the investigators report that much of the hard X-ray emission previously reported from the cluster actually originates in the single galaxy NGC 4388.

The large lifting capability of the Space Shuttle supported a significant advance in cosmic ray astrophysics by bringing up the 2000 Kg Cosmic Ray Nuclei Experiment (CRNE). An instrument of this extreme size and complexity was required to extend measurements of rare cosmic rays to energies almost 100 times greater than those previously studied by



comparable techniques. The investigators conclude that the cosmic ray flux arriving near earth becomes enriched with heavier nuclei, most notably iron, as energy increases. Another analysis presented energy spectra of the cosmic-ray nuclei boron, carbon, nitrogen and oxygen up to energies around 1 Tev, which yield information on the propagation of cosmic rays through the Galaxy.

Spacelab 3 carried an instrument, Ionization Status of Low Energy Cosmic Rays (IONS) to measure low energy "anomalous" cosmic ray ions. The abundances of sub-iron (Sc through Cr) and of iron were determined. The investigators conclude that the IONS measurement ratios are probably enhanced inside the earth's magnetosphere due to the degree of ionization of low energy Sc to Cr and Fe ions in galactic cosmic rays and to the filtering effects of the geomagnetic field. This is the suggested explanation of cosmic ray data previously cited as anomalous

The Astro 1 and 2 flights, using Spacelab pallets, carried an ensemble of astronomical instruments. Three of these, the Hopkins Ultraviolet Telescope (HUT), the Wisconsin Ultraviolet Photo-Polarimeter Experiment (WUPPE), and the Ultraviolet Imaging Telescope (UIT) operated in ultraviolet wavelengths and were mounted on the Instrument Pointing System.

A Broad-Band X-ray Telescope (BBXRT) with its own pointing system was added to Astro 1 with the initial motivation to observe a 1987 super nova, SN1987A, in a nearby galaxy. However, Astro 1 did not reach orbit until December 1990. The BBXRT was designed to make moderate resolution spectrophotometry of x-ray sources in the 0.3-12 keV band. It collected and published data for several astronomical objects, including Xi Pup, the Puppis A supernova remnant, and Cygnus X-2.

The HUT operations, particularly on Astro-2, were similar to that of a major ground based observatory. A list of several hundred observing targets was adopted to provide data to many investigators for a diverse analyses. The unique capabilities of this facility were used to make new far-UV observations of virtually every class of objects in the universe, a remarkable achievement! One of tasks the instrument was designed for was to detect and measure the characteristics of the primordial intergalactic gas. It so happens that the redshifted spectrum of quasar HS 1700 + 64 covered an absorption line of partially ionized helium. Thus by observing this redshifted spectrum, the concentration of intragalactic helium was measured for the first time.

The Wisconsin Ultraviolet Photo-Polarimeter (WUPPE) was conceived as a pioneering instrument for exploring polarization and photometry of astronomical objects in the ultraviolet spectrum. It too had a long observation target list of many different types of astronomical objects in the universe. During the two Astro missions, WUPPE obtained polarimetry and spectra for 121 objects.

The UIT is a 38-cm Ritchey - Chretien telescope equipped for ultraviolet filter and grating imagery over a 40 arc minute field of view with a resolution of about 3 arc sec. It produced ultraviolet (1200-3300 angstroms) images of a variety of astronomical objects,

particularly extended objects which are recorded on 70 mm film. This instrument produced an atlas of spatially -resolved mid-UV and far-UV images of 50 nearby galaxies. This set includes ellipticals, disk systems and irregular galaxies. Other extended objects studied include the Large and Small Magellanic Clouds and various star clusters.

The ASTRO missions produced over 167 publications in the astronomical and astrophysical journals. (A complete list is available on the ASTRO Website.) The surveys and catalogs generated from the Spacelab observations in previously unavailable frequency and energy ranges will find continuing utility in identifying individual astronomical objects worthy of future detailed study. This will insure a lasting legacy from Spacelab.

The evolutionary progress of instrumentation design afforded by the Spacelab missions was also an important contribution. While the Shuttle is not the ideal carrier for many astronomical instruments, it was a valuable test-bed for new observation techniques and opportunities. The resulting insight can subsequently be applied to free-flying observatories as the remaining astronomical issues warrant. Presumably, in the future, the International Space Station may provide a comparable test-bed for instrument concepts yet to be invented.

There has been a recent revolution in cosmology (see for example, "Revolution in Cosmology," *Scientific American*, Jan.1999) that began when two independent groups reported in *Science* evidence that the universe is expanding. A crucial starting point in any cosmological theory is the distribution of gravitating mass in the Universe and a key element to this is the cosmological baryon density. The measurements of singly ionized helium (He II) in the spectrum of the quasar HS 1700+64 with the HUT telescope on Astro-2 contributed directly to estimates of baryonic or ordinary matter generated in the big bang.

Also, the X-ray telescope on Spacelab 2 was a pioneering effort to use the measurements of X-rays from the intergalactic gas to assess the masses of galactic clusters. It demonstrated the usefulness of the technique, which requires spectral imaging of the clusters studied. Of course the duration and scope of observations from Spacelab 2 was limited by the mission length. In 1990, five years after Spacelab 2, the ROSAT satellite was launched with X-ray spectral imaging capabilities. Far more comprehensive observations of galactic clusters were obtained and analyzed. These later data, building on the Spacelab 2 experience, currently provide one of the best measurements of observable mass in the universe, since galactic clusters represent a large fraction of the identifiable mass.

The noteworthy point here is that pioneering investigations using Spacelab instrumentation helped move the cosmology discipline to its current exciting state.

## Solar Physics

The scientific investigations carried out by solar experiments using the Spacelab facility fall into three main categories; measurements of the solar irradiance (the solar constant problem), abundance determinations (the solar helium problem), and the dynamic nature of the solar atmosphere.

The solar constant is not really a constant. Small, but persistent variations in the solar input to the Earth's atmosphere, oceans, and land masses can have dramatic effects and can possibly explain a wide range of past climatic changes. To determine the effects of variations in solar input, it is essential to monitor solar irradiance over long intervals and to understand the physical basis for its variations. This task is best carried out on unmanned satellites that can remain in orbit more-or-less indefinitely. The Spacelab missions have been used to test and calibrate new instruments before committing them to unmanned satellites and to provide periodic checks on the calibration of similar instruments already on free fliers. Short duration missions have the distinct advantage of being able to calibrate an instrument just before and just after a flight.

The total solar irradiance was measured using the Active cavity Radiometer Irradiance Monitor (ACRIM) and the Measurement of the Solar Constant (SOLCON) instruments. The SOLCON measures the absolute irradiance integrated over the entire solar spectrum, while the ACRIM measures the absolute irradiance from the ultraviolet to the infrared. ACRIM was first flown on Spacelab 1 and was later flown the Solar Max satellite. Each of the ATLAS missions carried an ACRIM and a SOLCON instrument. SOLCON was also flown on the ESA retrievable platform, EURECA.

Solar ultraviolet radiation in the wavelength range 120 to 400 nm is absorbed by the Earth's atmosphere between 20 and 120 km and even though this radiation constitutes only a small percentage of the total solar output, it is the main source of energy for the middle atmosphere. This ultraviolet component of sunlight varies considerably more than the visible radiation. During an 11-year cycle of the Sun's activity, changes in ultraviolet radiation bring about corresponding changes in a number of atmospheric conditions and may be responsible for weather and climate changes. This region of the spectrum is monitored by the Solar Ultraviolet Spectral Irradiance Monitor (SUSIM). SUSIM was flown on Spacelab-2 and on each of the ATLAS flights. Measurements from these flights are compared with the same instrument on the Upper Atmosphere Research Satellite (UARS).

The Solar Spectrum (SOLSPEC) measures the solar spectrum from the infrared through the ultraviolet to obtain spectral variations over the entire optical spectrum. This instrument was also flown on each of the ATLAS missions.

The abundance determinations and the dynamic nature of the solar atmosphere were carried out using the Coronal Helium Abundance Spacelab Experiment (CHASE), the Solar Ultraviolet High Resolution Telescope and Spectrograph (HRTS), and the Solar Optical Universal Polarimeter (SOUN). These instruments were flown on Spacelab-2.

The Solar Physics investigations on the Spacelab missions resulted in 28 publications in refereed journals.

## Space Plasma Physics

When an object as large as the Shuttle moves through the residual atmosphere at nearly 8 Km/s, it generates many complex interactions with both the neutral and ionized components. Several of the Spacelab flights carried a variety of instruments to probe the responses of the surrounding ionospheric plasma environment to these perturbations. It has also been possible to conduct experiments that actively modified this environment in order to learn more about the dynamics of the Earth's ionosphere.

Visible evidence of such interactions were observed on the very first Shuttle flights when a glow was noticed on the Shuttle surfaces interacting with the atmosphere in the ram direction. It was found that this glow emission had intensities which were comparable to that of the Earth's airglow and to the brightness of stars in TV cameras.

Although most of the Shuttle based space plasma science was oriented towards actively stimulated effects, an electron spectrometer experiment aboard Spacelab 1 was used to measure fluxes of low-energy electron precipitation at low latitudes (below the Van Allen belts). In addition to a low energy component with a power law spectrum, they found a high energy peak that at times showed temporal flaring with time scales of about 1.5 hours. A likely acceleration mechanism for these electrons has still not been identified.

Spacecraft charging was measured during the STS-3 (OSS-1) mission using instrumentation of the Vehicle Charging and Potential (VCAP) experiment. Charging measurements using thermal plasma probes were obtained during passive events as well as periods when a 100 mA at 1 keV electron beam was emitted. An upper limit of about 1 mF was obtained for the Shuttle's capacitance. Under steady state conditions, the electrical potential typically reached only a few volts, although during some nighttime conditions, potentials of over 40 Volts were detected.

The Space Experiments with Particle Accelerators (SEPAC) was a joint endeavor between NASA and the Institute of Space and Aeronautical Sciences (ISAS) in Japan. Its objectives were to investigate beam-atmosphere interactions and beam-plasma interactions in the Earth's upper atmosphere and ionosphere. It was found that the magnetoplasma dynamic (MPD) arcjet was effective in maintaining vehicle charge neutralization during electron beam firings, but only for a brief period of 10 ms or so. Therefore, a xenon plasma contactor, which can provide continuous vehicle charge neutralization, was developed for the ATLAS 1 SEPAC experiments.

One of the important investigations from Spacelab 2 was of the creation of "artificial holes" in the F-region ionosphere. These holes are the result of rocket launches as well as shuttle engine burns supplying various contaminants in large amounts to react with the ambient  $O^+$ , producing a new ion and neutral. The ions subsequently recombine rapidly with electrons to form neutral molecules and airglow. Hence the plasma density is rapidly depleted, creating a hole in the ionosphere. The artificially-induced hole resulting

from a Shuttle engine firing was observed as a burst in the airglow over New England on July 29, 1985. Another Shuttle engine burn over the Hobart observatory in Australia on August 5, 1985, created a "window" in the ionosphere which allowed much lower than normal frequencies to be observed from the ground observatory. Such observations were described as being useful in permitting much improved mapping of the galactic radio distribution, particularly at frequencies below 1.6 MHz.

A deployable Plasma Diagnostics Package (PDP) was developed in order to probe the plasma, field and wave environment of the Shuttle. This instrument proved invaluable in the beam-plasma experiments conducted on OSS-1, Spacelab-2, and ATLAS-1 as well as the ionospheric perturbations caused by the Shuttle. From data taken from the PDP it was estimated that the Space Shuttle was producing a water vapor cloud with densities of the order of perhaps  $10^9$  H<sub>2</sub>O molecules/cm<sup>3</sup> at approximately 50 m from the Shuttle. Additional observations of water and other ions during Spacelab 2 were obtained with a Bennett RF ion mass spectrometer on the PDP. They found that the concentrations of the water ions decreased with distance from the Shuttle in the orbiter wake, and fell below the concentrations of ambient O<sup>+</sup> ions at wake distances of about 30 m. These and other similar measurements raised serious questions about the viability of making reliable natural or ambient ion measurements in the Shuttle environment.

The plasma environment of the wake of the Space Shuttle for Spacelab 2 mission was investigated with the PDP. It was found that the plasma densities decrease within the deep wake much faster than the rates predicted by previous theoretical models. The densities were, for some regions, an order of magnitude or perhaps more lower than the theoretical predictions.

One of the most exciting opportunities for the space plasma investigations was the creation of artificial auroras by means of electron beam injections fired down upon the atmosphere by SEPAC electron accelerators on the Shuttle orbiter. With the hollow-cathode Xenon plasma contactor, beam currents, of up to 1.2 Amps could be maintained. Some 60 artificial auroras were created over the South Pacific. They were observed from the ground as well as with the Atmospheric Emissions Photograph Imaging (AEPI) instrument onboard ATLAS-1.

Early on, it was recognized that the use of a tether connecting a sub-satellite to the Shuttle could enable some intriguing electrodynamic and space plasma experiments, using a long conducting wire. The Tethered Satellite System (TSS) was a partnership venture between NASA and the Italian Space Agency (ASI). The second flight of the TSS hardware was the TSS-1R mission, which involved the deployment of a 1.6 m diameter spherical, conducting satellite, connected by a electrically-conducting tether, the tether being insulated from the ionospheric plasma. There were twelve science investigations, several of which were designed to explore space plasma-electrodynamic processes, particularly involved in the generation of ionospheric currents. One of the major surprises of the TSS-1R mission was in the current collected by the TSS versus the voltage which exceeded theoretical expectations by factors of 2-3.

Thus far, 140 publications in the refereed literature have resulted from these investigations.

## Atmospheric Science

The study of the troposphere and stratosphere is intimately linked with human activities, and several studies focused on the detection of and monitoring of transport of atmospheric pollutants on a global scale. We now know, for example, that widespread burning of grasslands and forests in South America, Africa, and Australia are major sources of carbon monoxide and ozone in the southern hemisphere, observed to travel between continents and across oceans. Spacelab investigations also tracked the spread of industrial pollutants between continents as well, underscoring the global nature of these problems.

Some of the instruments involved in the study of atmospheric physics from various Spacelab missions and the contributions they made are described in the following.

The ATMOS is a Fourier transform infrared spectrometer that is designed to study the chemical composition of the atmosphere by observing their absorption spectra when the atmosphere is between the Sun and the instrument. The primary objective for the ATMOS experiment is to make simultaneous measurements of as many trace atmospheric constituents as possible and to provide height-volume mixing ratio profiles of these gases. It was flown on OSTA-3, Spacelab 3, ATLAS-1, ATLAS- 2, and ATLAS-3. Observations of vertical profiles of stratospheric trace gases not previously measured, including  $\text{N}_2\text{O}_5$ ,  $\text{ClONO}_2$ ,  $\text{HO}_2\text{NO}_2$ ,  $\text{CH}_3\text{Cl}$ ,  $\text{COF}_2$ , and  $\text{SF}_6$  were made by this instrument. The following is a quote from the ATMOS team,

"Today we are aware of some 40 different molecular species in the atmospheric inventory, all of which play a role in the chemistry of the atmosphere and in its interaction with the Sun's radiation. In the past decade, research into many interrelated questions about the Earth's atmosphere has made scientists aware of the complexity of the processes that affect it, and has drawn attention to the need for more detailed studies in order that these processes can be better understood. This, in turn, has shown the need for a means by which global measurements can be made of the composition and temperature of the atmosphere and their variability."

The GRILLE Spectrometer flown on Spacelab 1 and Atlas 1 works on the same principle as ATMOS. Study altitude. It measures absorption and emission profiles of molecules on a global scale in the stratosphere and mesosphere.

The Imaging Spectrometric Observatory (ISO), flown on Spacelab 1 and Atlas 1, measures thermospheric emissions over a broad wavelength range (extreme ultraviolet to near infrared). ISO studied the chemistry/photochemistry of the mesosphere and thermosphere. It was also used in several studies that helped quantify the initially baffling problem of identifying the source of the 'shuttle glow' that interfered with remote sensing investigations from space. The instrument development effort for this investigation lead to new instruments, including a compact spectrometer and the Ultraviolet Imager (UVI),



currently operational on the GGS POLAR spacecraft. In the delay following the Space Shuttle Challenger accident, the ISO was used as a ground observatory from McDonald, Texas. ISO obtained the first spacebased measurement of ground state OH in the mesosphere, the first dayglow altitude profiles of  $N(^2P)$  at 346.6 nm (which provided the first examination of photochemical sources and sinks in normal daytime thermosphere uncontaminated by auroral emissions), and the first simultaneously acquired altitude images of NO gamma band temperature and intensity in the thermosphere.

The Atmospheric Lyman Alpha Emissions (ALAE) was flown on Spacelab 1 and ATLAS-1. The instrument is a spectrophotometer that measures the absolute intensity of the deuterium emissions. Measurement of the Lyman  $\alpha$  emission of deuterium atoms offers a new possibility to probe the chemically active region where  $H_2O$  (and HDO) is photodissociated, the D atoms serving as the most appropriate proxy to the H atoms which cannot be observed directly. The AEPI also provided observations of gravity waves, not by building up data, but by two-dimensional imaging of the airglow emissions.

Measurement of Air Pollution from Satellites (MAPS) was flown on OSTA-1, OSTA-3, and on SLR-2. The MAPS experiment measures the global distribution of carbon monoxide (CO) mixing ratios in the free troposphere. The MAPS instrument made observations of biomass burning in the South American Amazon Basin and southern cerrados, the African savannahs, and the Australian grasslands and ranches to demonstrate that forest burning in remote locations can contribute to enhanced CO and  $O_3$  levels that can be transported large distances from the burn sites. These data were responsible for finding that carbon monoxide concentrations in the troposphere are highly variable around the planet, and that widespread burning is a major source of carbon monoxide in the southern hemisphere and tropical troposphere.

The Millimeter-wave Atmospheric Sounder (MAS), flown on ATLAS-1, -2, and -3, is a shuttle-based, limb-scanning spectrometer. It measures emissions from six mm-wave transitions of four molecular species:  $O_3$ ,  $H_2O$ , ClO, and  $O_2$ . MAS. From these measurements, abundance profiles and temperatures are deduced. The MAS performed the first measurements of latitudinal variation of mesospheric nighttime  $O_3$  and  $H_2O$ , an accomplishment that is also an example of the next class of observations: observations conducted on an extended scale.

The Shuttle Solar Backscatter Ultraviolet (SSBUV) has been flown on a large number of Shuttle missions, including OSTA-1, OSTA-3, Spacelab-1, Spacelab-2, ATLAS-1, ATLAS-2, ATLAS-3, and USMP-2. The SSBUV flights support the long-term global stratospheric ozone and solar UV monitoring programs by providing repeated checks on the calibrations of UV ozone and solar monitoring instruments flying on US and international satellites. The SSBUV's value lies in its ability to provide highly accurate ozone measurements. The instrument is calibrated to a laboratory standard before flight, then is recalibrated during and after flight to ensure its accuracy. These laboratory standards are calibrated routinely at the National Institute of Standards and Technology.

The rigorous calibration has been maintained since the beginning of the SSBUV flight series.

The SSBUV instrument detected and verified a significant decrease in the amounts of total Northern Hemisphere between the ATLAS-1 (March 1992) and ATLAS-2 (March 1993) missions. This depletion also was detected simultaneously by satellites and ground-based observations. Indications are that total ozone decreased during the same period on the order of 10 to 15 percent at mid-latitudes in the Northern Hemisphere. Scientists believe that this significant depletion resulted from the combined residual effects of Mt. Pinatubo aerosols in the stratosphere and cold stratosphere temperatures during the winter of 1992/93.

The Cryogenic Infrared Spectrometers and Telescopes for the Atmosphere (CRISTA) with the Middle Atmospheric High Resolution Spectrometric Investigation (MAHRSI) flew on the German Space Shuttle Pallet Atmosphere Satellite (CRISTA/SPAS), as part of the ATLAS-3 mission. CRISTA acquires global maps of temperature and atmospheric trace gases with very high horizontal and vertical resolution. MAHRSI's primary objective is to measure limb intensity profiles of the resonance fluorescent scattering of sunlight by hydroxyl (OH) in the altitude region from 38 to 90 km, and by Nitric Oxide (NO) in the region from 48 to 160 km. The CRISTA-SPAS platform is deployed using the Shuttle manipulator arm and traveled some 50-100 km behind the shuttle. After 8 days it was retrieved and returned to Earth.

The ATLAS-3 mission was complemented by The CRISTA/MAHRSI Campaign to provide ground truth and other coordinated measurements including monitoring of the atmospheric background by ground based, aircraft, balloon, rocket and satellite experiments. The first campaign took place from October 27 - November 25, 1994 and included over 32 rockets, 56 balloons, and ground based experiments at 42 locations. A second campaign was carried out in support of CRISTA 2 which was deployed from STS-85.

Altogether, the atmospheric studies from the Spacelab missions have resulted in 199 papers in refereed journals. The scientific contributions to atmospheric science from the Spacelab missions can be summarized as:

- A greater understanding of the chemistry and transport of the atmosphere, from the lower troposphere to the upper thermosphere, but with greatest emphasis on stratospheric trace gases and especially stratospheric ozone. The contribution from these investigations can be grouped into four categories: observations made for the first time or of a unique event, observations made over an extended period of time or an extended spatial extent, observations detailed enough to provide heretofore unavailable constraints for model development and investigation, and correlative observations with other investigations.
- Increased knowledge of the impact of human activities on the lower atmosphere. Examples include transport of pollutants (both industrial and from biomass burning)

across continents and oceans. This category can also include the studies of the optical glow environment of the space shuttle, since this must be understood and corrected for in any shuttle-based remote sensing investigation.

- Unprecedented opportunities for correlative studies and validations between multiple observing platforms, which are vital for quantitative atmospheric studies.

Do we now view the atmosphere in a fundamentally, or revolutionarily different manner because of the Spacelab investigations? In the large picture, probably not much. But in the details, undoubtedly so. Atmospheric models, and our understanding, are now constrained to match a new wealth of observations. This is the principal contribution of the Spacelab atmospheric investigations.

## Earth Observations

The dual Spaceborne Imaging Radar-C (SIR-C)/X-band Synthetic Aperture Radar (X-SAR) was flown aboard the Shuttle Endeavor during the April and October 1994 missions, SRL-1 (STS 59) and SRL-2 (STS 68). The SIR-C system records data at both L-band (23.5 cm) and C-band (5.8 cm) with full polarimetric scattering; while the X-SAR is capable of recording data in the X-band (3.1 cm) with copolar polarization only. The integrated system records data simultaneously at incidence angles ranging from 15-60° with image resolution varying from 10 to 50 m depending on system configuration. The SIR-C/X-SAR is a considerably more advanced airborne imaging radar compared to satellite mounted instruments such as the European Remote Sensing Satellites (ERS-1,2), the Japanese Remote Sensing Satellite (JERS-1), or the Canadian RADARSAT and has more than 1000 times their spatial resolution.

The impact within the remote sensing and earth science communities of the two SIR-C/X-SAR missions was demonstrated early on by the large number of sessions and papers devoted to the subject at the 1995 International Geoscience and Remote Sensing Symposium (IGARSS'95) sponsored by IEEE. Significant interest carried over to the subsequent IGARR Symposia in 1996, 1997 and 1998 as well. Subsequently, three major journals within the earth science and remote sensing communities devoted special issues to presentation of the results of the missions. These issues were *IEEE Transactions on Geoscience and Remote Sensing*, 33(4), 1995; *Journal of Geophysical Research*, 101(E10), 1996; and *Remote Sensing of Environment*, 59(2), 1997. In addition, most of the investigators associated with the missions have published significant articles in journals within their specific disciplines and dozens of other scientists not directly associated with the original missions have incorporated the data into their research and continue to publish results. So far 117 papers related to these two flights have appeared in the open literature.

Following the flights of the SIR-C/X-SAR in 1994, NASA requested the Space Studies Board of the National Research Council (NRC) to evaluate the utility of a third SIR-C/X-SAR mission and to provide guidance in developing a strategy for a small space-based, science-oriented, interferometric SAR. As a result of this report, and the apparent success of the SIR-C/X-SAR missions, NASA has issued a call for proposals for investigators to participate in mission planning and design of the Lightweight Synthetic Aperture Radar (Lightsar) to be launched in 2001 or 2002. Lightsar will be a low orbiting imaging radar satellite operating in the L-band with full polarimetric scattering, and possibly in C- or X- band as well. Thus, the parametric design standards and mission goals of Lightsar build directly on the results of the SIR-C/X-SAR investigations.

The earth science applications associated with SIR-C/X-SAR data can be grouped into six broad categories: Oceanography (including wave observations); Ecology (forestry, agriculture, wetlands); hydrology; geology and geomorphology (including volcanology); precipitation and climate (including glaciology); and surface mapping and topography.

## **Oceanography**

The oceanographic studies associated with the SIR-C/X-SAR missions consisted of investigations of the capability of the system to measure important wave properties such as significant wave height (SWH), wave number and propagation direction; and to observe surface frontal boundaries separating cold and warm water masses. An on-board processor developed at Johns Hopkins University produced real time images of ocean wave spectra from the C-band signal. A primary goal of the wave study was to incorporate these real time observations into a numerical wave model in order to correct and update model predictions in real time.

The principal development of the wave studies appears to be the conclusion that low orbit radar data can sufficiently distinguish important wave properties in real time such that they can be used to improve numerical wave forecast models. Improved wave forecasting would be very valuable in many instances, including severe weather situations such as hurricanes, or in cases of waves generated by tsunamis.

Another result of the ocean studies was that frontal boundaries were identified on the SAR images during the October flight and that these boundaries closely agreed with field observations and data obtained from conventional thermal and infrared satellite sources. Boundary movement was also successfully observed by using images from successive shuttle overpasses. Frontal boundary location and movement can have important consequences in terms of weather occurrence and fisheries productivity as well as on water quality issues such as hypoxia and algal blooms. However, the advantages of observing frontal characteristics from microwave radar measurements in lieu of currently available thermal and infrared instruments is unclear.

## **Ecological Investigations**

The ecological studies associated with the SIR-C/X-SAR missions can be grouped into three categories: forestry, wetlands, and forest/nonforest land use classification. The forestry studies consisted primarily of classification and mapping forest spatial structure, classification of growth stages and above ground biomass estimation. Forestry studies were focused on both northern latitude hardwoods in Michigan, Maine, Germany, and the southern rainforests of Brazil. Attempts were also made to combine forest growth models with a radar backscatter model to improve image analysis.

Reported results using the SAR data for forest spatial classification were decidedly mixed. The spatial structure recognized on the SAR images was successfully related to forest management practices such as logging or storm damage. The range of results on classification and spatial mapping of forest types is at least partially due to the different physical and environmental conditions at the various sites. Some sites were in cold regions, others were in southern rainforests; some were in flat terrain while others were in mountainous regions, in some cases snow covered the canopies while in others it did not. These results appear to show that classification and mapping algorithms for SAR data

can accurately distinguish broad classes, but that algorithms that would be generally applicable over a range of conditions may be difficult to develop.

The results for biomass estimation from SIR-C/X-SAR data were fairly consistent even though environmental factors are known to affect these estimates as well. The results appear to show that forest biomass can be predicted using with sufficient accuracy over a variety of environmental conditions to allow radar data to be used as a significant forest management tool. Forests cover a substantial portion of the earth's surface and the carbon contained in their biomass is an important component of the global carbon budget. The success of these missions in predicting forest biomass clearly indicates the importance of active microwave measurements in analysis of the global carbon cycle.

Wetland analyses focused on identification of wetland flooding cycles during the dry (April) mission compared to the wet (October) mission over the Yucatan Peninsula. Changes from dry or partially flooded to complete inundation could be easily detected; however, changes from dry to partially flooded could not be detected by any configuration. Based on the radar configurations tested, it was concluded that a combination of ERS-1 and 2, and Radarsat might function to detect seasonal flooding of most wetlands, excluding partial flooding.

Land use classification investigations focused primarily on discrimination between forest and non forested areas. In all of these analyses, under differing environmental and physical conditions, the SAR data were uniformly successful in separating forest from non-forest areas. Accuracies ranged from 87 % to nearly 100%. The ability of active microwave measurements to discriminate forested areas, as well as forest classes, and to accurately estimate forest biomass and carbon storage, makes this technology extremely promising as a tool in global change analysis.

## **Hydrology**

The hydrologic investigations associated with the subject missions dealt with the capability of the SIR-C/X-SAR data to estimate soil moisture under a variety of soil types, surface roughness, and moisture conditions and to map the spatial structure and estimate equivalent water content of non-glacial snow pack. The estimation of soil moisture content from remote sensing sources has thus far been an intractable problem in hydrology and has become a major focus of research ). Most of this research has focused on the use of visible-near IR or passive microwave instruments. Problems with this approach include the relatively coarse spatial resolution of these instruments and their ability to only sense the surface moisture. Active microwave instruments do not exhibit these problems, and consequently, their employment in hydrology is one of the most promising developments in recent years. The SIR-C/X-SAR missions offered the first opportunity to use multi-frequency, multi-polarization airborne data to study soil moisture signals over a variety of climates, vegetation and soil types ranging from Manitoba, Canada to Oklahoma, USA, to Orgeval, France. For this reason, it potentially represented a major step in the development of algorithms to relate vertical soil moisture profiles to radar backscatter.

The shuttle missions coincided with major field campaigns to measure soil moisture in Manitoba, Canada, the Little Washita basin in Oklahoma and the Orgeval watershed in the Brie region of France. Given the ability of the longer wave length radar signals to penetrate the soil surface, active microwave instruments have the potential to measure not only surface soil moisture content, but vertical soil moisture profiles as well. Unfortunately, observed backscatter signals are influenced not only by the soil properties of the surface under investigation, but also by the surface topography, roughness and vegetation characteristics. Past research has focused on the use of these data to estimate moisture profiles primarily on bare soil under relatively smooth surface conditions. Effective algorithms have yet to be developed to correct the radar backscatter signal for variations in surface roughness or vegetation. The two SIR-C/X-SAR missions had the potential to lead to significant improvements in current methodologies; however, this potential does not seem to have been fully realized as of yet. As the data collected during the missions are obviously still available, it is hoped that some of the more important problems associated with remote sensing of soil moisture, *i.e.*, vertical profile estimation throughout the active zone and correction for vegetative cover and surface roughness will continue to be addressed in future research. Until this is done, operational use of remote sensing instruments for soil moisture estimation will not be realized.

The results of the snow pack experiments may have more immediate practical applications than do the soil moisture investigations. The ability to map snow cover and to estimate the equivalent water content of snow packs can be a great aid in the estimation of spring snow melt runoff from mountainous regions. Snowmelt provides the essential runoff for replenishment of reservoir stocks in many parts of the world (e.g., the western United States). The ability to accurately estimate the volume of this runoff in advance would be a great benefit to hydrologists, hydropower operators and water supply managers. The SRL-1 and -2 missions demonstrated the ability of multi-frequency, multi-polarization data to accurately discriminate between snow covered and non-snow covered regions in areas of high topographic relief (without the aid of topographic maps) and to estimate equivalent water content of snow cover. Ratio backscattering coefficients at the different frequencies could be adjusted to enhance the images and the estimated wetness values compared well with ground observations over the test site. It was also demonstrated that different frequencies (35 GHz and 5.3 GHz) could be employed to discriminate between layers of snow pack based on temperatures and wetness.

### **Geology and Geomorphology**

The geological and geomorphological investigations associated with the missions focused on observation of sand covered features in Arabian deserts, mapping of volcanic lava fields and observations of associated deformations and mapping of alluvial flood plains. The restricted range of wavelengths of the SIR-C/X-SAR instruments (3.1 cm - 23.5 cm) limits the penetration range of the beams and thus restricts the application of the system in subsurface investigations. The L-band copolar (HH) data was used to penetrate up to 4 m of sand in the Arabian Peninsula to reveal older geologic features such as drainage channels. The X-band (VV) data could also penetrate up to 3 m of sand. The C and L-

band data were employed in an Egyptian desert overlain with a shallower (2 m) sand layer and produced enhanced images that were able to reveal deeper rock formations and fractures, along with shallow quaternary drainage channels. These results suggest that L-band copolar data at small incidence angles may be able to detect shallow groundwater deposits in arid regions- a potentially valuable contribution.

The volcanology investigations focused on analysis of lava fields and geologic structure and deformation of volcanoes in southern Italy and Kilauea Volcano, Hawaii. C and L-band copolar (HH) and cross polar (HV) data revealed lava fields of different ages (5000 years and 10,000 years) and were able to separate lava fields from undisturbed areas. In the Lattari and Picentini mountains, three sets of geologic lithologies were identified and fault lines were clearly evident on the images. The Kilauea Volcano studies attempted to measure the deformation that occurred in the time span between the two missions, as well as short term (daily) deformation between successive passes on the same missions. A vertical deformation of up to 14 cm was observed over an area of several km<sup>2</sup> around the volcano in the time between the two flights. Comparisons with GPS field measurements showed that while the maximum deformation agreed to within 2 mm, estimates of the deformation did not correspond to the field measurements at any one point in the field, implying that the radar data can detect general deformation trends over large areas, but not exact geographical values. It was also found that the L-band data was superior to the C-band for vegetated areas for these analyses.

C and L-band multi-polarization data were also used to map areas of flooded forests in the Amazon rainforest and to discriminate between vegetation classes corresponding to water tolerance. This study was part of an ongoing investigation to quantify methane fluxes and production of Amazon rainforests. Vegetation classes corresponding to different rates of methane production were successfully identified.

### **Precipitation and Climate**

Precipitation and climate studies focused on the use of multifrequency, multipolarization radar data to estimate rainfall rates and classify precipitation types and to observe glacier dynamics. The shuttle missions afforded the unique opportunity to observe storm dynamics associated with Cyclone Odille (April, 1994) and Typhoon Seth (October, 1994) using a variety of radar frequency/polarization configurations. Quantification of rainfall rates was approached as an inversion problem, *i.e.*, to estimate the radar parameters most likely to have produced the observed scattering profile. As such, the collected data provided an opportunity to develop and test inversion algorithms to be employed with the Tropical Rainfall Measuring Mission (TRMM) satellite that was launched in 1997. Rainfall profiles were obtained from the C-copolar (VV) and X copolar (VV) scatterometer data. The inversion algorithm demonstrated that rain rates could be estimated within small error bounds at higher altitudes (> 7 km), but that error increased greatly at lower altitudes and was greatest at heights less than 5 km. Rainfall mechanisms could also be accurately discriminated, as convective rainfall was separated from stratiform dynamics.



There is a relationship between glacier dynamics and long term climate change. Northern latitude glaciers in Austria were studied as well as southern glaciers in Chile. The focus of the studies was to map the extent of the glaciers, estimate ice velocities, observe glacial calving (separation), and attempt to identify areas within the glacier field of accumulation or ablation. In some cases, equivalent water content of glacial snowpack was also estimated. Glacier dynamics are studied by radar interferometry; the phase differences between two images acquired at different passes at the same incidence angle are related to the surface displacement of the glacier. In this case, the L-band and C-band data were acquired on each pass at a spatial resolution of about 30 m, and the interferograms were computed for each band. Image analysis can be employed to determine the direction and rate of ice flow and to identify areas where ice is accumulating or abating. The Moreno Glacier in the southern Patagonia icefield showed a displacement of about 17 cm/d over the period of the October mission to an accuracy of 2 cm/d, and that the glacier shows a net annual accumulation of 5540 mm of equivalent water to an accuracy of  $\pm 500$  mm.

### **Surface Mapping and Topography**

The surface mapping investigations associated with the April and October 1994 shuttle missions were focused on the development of relationships between measured backscatter from the SIR-C/X-SAR radars and surface roughness and topographic characteristics. A foreground/background inversion scheme was able to separate surface roughness signal from background noise through filtering of the different radar frequencies. However, the signal to noise relationship was a significant function of roughness scale and frequency. Large scale features could be accurately identified as could small scale features to some degree. Intermediate scale features were more difficult to identify. It was possible to identify four levels of surface features from the data; however, it was concluded that a stable algorithm must sacrifice roughness resolution.

### **Summary and Conclusions**

Due to the nature of earth science investigations, it is not to be expected that some fundamental breakthrough in understanding of the physical or biological processes under observation could be realized from one or more short term remote sensing missions. The measurements obtained during these missions represent mere snapshots of the processes under the particular set of environmental conditions which prevail at the time of the missions. Thus, fundamental knowledge of the processes must be gained from repeated observations under the full range of conditions which can occur at the test sites, and enough sites must be tested in order to gain sufficient information to make informed inferences. This is necessarily a slow and tedious process. However, progress can be made from discrete missions such as the two SIR-C/X-SAR flights in three categories:

- Clear demonstrations of the capability of active microwave instruments to measure some processes that have important scientific or practical value, and thus provide impetus for further mission or satellite development.

- Development and testing of algorithms that can be employed with current satellites or other instruments to enhance their productivity or usefulness.
- Advance basic algorithm development to use microwave backscatter measurements to observe and understand important physical or biological processes with scientific or practical implications.

It is clear that the SIR-C/X-SAR missions made significant contributions in all three of these areas. Clearly, the most important of these is the very significant results in the first category. In the areas of forest mapping and biomass estimation, ocean wave observations, rainfall quantification, snow cover mapping and estimation of water content, glacier observations, and crustal deformation associated with volcanoes and earthquakes the SIR-C/X-SAR results provided convincing evidence of the ability of the instruments to provide accurate measures of quantities associated with these important processes. The results of these missions contributed significantly to the utility of the Tropical Rainfall Measuring Mission (TRMM) satellite launched in 1997 to observe and quantify tropical rainfall and to the decision by NASA to design and launch an active microwave satellite (Lightsar) within the next two years. The operation of these satellites has the potential to make tremendous contributions to basic science and may have great practical impact on the lives of the people of the United States and elsewhere.

# Microgravity Sciences

## Microgravity Fluids and Combustion Research

The study of the behavior of fluids in microgravity is fundamental to the understanding of virtually all other microgravity sciences since the suppression of fluid flows resulting from buoyancy effects is the primary reason for most microgravity experiments. (The exceptions being cases in materials science where the hydrostatic head may cause deformations in extremely weak solids or in the life sciences where there is evidence that the unloading of the cytoskeleton may be responsible for altered cellular behavior.) As a result, many of the fluids experiments were aimed at providing information to support the materials science experiments. One of the striking features in much of the research on the behavior of liquids in space is the importance of capillary or interfacial phenomena after buoyancy effects are essentially removed. Clearly these phenomena are present in normal gravity, but are usually neglected because their effects are often masked by buoyancy-driven flows. The ability to uncouple gravity effects from non-gravitational effects, so that the latter can be studied in more detail, has been one of the primary justifications for the study of fluid phenomena in microgravity.

Combustion experiments in microgravity are a special case of fluid experiments in which chemical reaction must be included. However, the motivation for performing this class of experiments in space is basically the same; the need to separate gravity-related from non-gravity related effects and to use the simplifications obtained by effectively eliminating convective transport in order to gain a better understanding of the basic principles involved. It is also important to understand combustion in the virtual absence of gravity to develop design criteria and emergency procedures for dealing with fire safety in the operation of manned laboratories in space.

### Capillarity Effects

Capillarity effects are responsible for liquids wetting and spreading over surfaces (or failing to wet and spread). Water will rise in a clean glass capillary tube as the surface tension pulls the column of water up the tube until its force is balanced by the weight of the column. Without gravity, the liquid will continue to rise until it fills the tube. However, this can only happen if the water wets the surface. By this, we mean that the presence of the water lowers the surface energy of the glass such that the free energy of the system is reduced. Mercury, for example, does not wet glass, hence a column of mercury is forced downward in a capillary tube.

Atoms or molecules in the interior of a solid or liquid have molecular bonds with their nearest neighbors which lower their energy. (Energy must be added to vaporize the material in order to free these molecules.) All surfaces have an excess of energy (compared to their interior) because some of the bonds are not satisfied owing to the lack of nearest neighbors. In the case of water on clean glass, the water molecules partly satisfy the bonds on the surface of the glass, but there is still an excess of energy, called

the interfacial energy, due to the fact that the water-to-glass bond is not as strong as glass molecule bonds. Of course, the water also has a surface energy (which in liquids is called the surface tension), so it costs energy for the liquid to spread over the solid. Under static conditions, in the absence of other forces, the configuration of a drop of liquid on a solid is determined by the balance of the forces associated with these surface energies. The contact angle, which is the interior angle between the liquid and solid, is related to the surface energies by Young's equation,  $\gamma_{LV} \cos \theta = \gamma_{SV} - \gamma_{LS}$ , where  $\theta$  is the contact angle,  $\gamma_{LV}$  is the liquid-vapor surface energy or surface tension,  $\gamma_{SV}$  is the solid surface energy and  $\gamma_{LS}$  is the interfacial energy between the liquid and the solid. One may see that the contact angle will be less than  $90^\circ$  when the liquid-solid interfacial energy is less than the solid-vapor surface energy and we say the liquid wets the solid. If the liquid-solid interfacial energy is greater than the solid-vapor surface energy, as is the case between mercury and glass, the contact angle is greater than  $90^\circ$  and the droplet tends to bead up on the solid surface. (Under certain conditions, in the absence of gravity, the droplet will actually be repelled from the surface.). If the sum of the solid-liquid interfacial energy and the surface tension is equal or less than solid-vapor energy, the contact angle goes to zero and the liquid will spontaneously spread over the solid surface. Such a liquid is said to be perfectly wetting.

In normal gravity, the hydrostatic energy generally overwhelms the capillarity forces; hence their effects are manifested only in the vicinity of the liquid-solid wall contact where they form a meniscus. However, in microgravity capillarity forces determine how a liquid will be distributed in a partially filled container. The situation becomes more complicated under dynamic conditions in which the contact line is required to move. There is a sort of static friction or stiction that tends to restrict the motion of the contact line and this stiction depends on whether the contact line is advancing or receding. It becomes important to understand how these forces operate in order to be able to design fluid systems that will operate predictably in space. Examples include being able to control the distribution of fuel in a tank or designing an anti-spread barrier to restrict the motion of a liquid in an open container.

A variety of experiments were conducted in which the configuration of liquids in a partially filled container was observed as the container was rotated and shaken. The results were compared against computer models to determine how well such effects could be predicted. One particularly interesting set of experiments involved the behavior of liquids in chambers in which the fluid configuration was mathematically indeterminate (e.g., different configurations had the same configurational energy) in order to see how nature would deal with this situation.

### Floating Zones

Microgravity offers the possibility to conduct experiments with free liquid surfaces on a scale not possible on Earth. One process of interest to materials scientists is the use of a floating zone for crystal growth. A molten zone is created in a rod of feed material and is traversed along the rod. New feed material enters the advancing zone and a single crystal

can be grown at the receding interface. The melt is supported by its surface tension, thus eliminating any wall contact, which could contaminate the melt and induce various growth defects. Unfortunately, the size zone that can be supported by surface tension is limited to only a few millimeters in normal gravity.

Of primary interest is the stability of such zones. More than 100 years ago, Lord Rayleigh showed that a cylindrical liquid column would become unstable and break if the length exceeded the circumference. But what happens if the zone is not cylindrical? Or vibrated by mechanical disturbances in the spacecraft? Or if it is rotated, which is sometimes done to even out asymmetries in heating? Many of these questions had been approached theoretically and experimentally using neutrally buoyant immiscible liquids similar to the work carried out by the Belgium physicist, Plateau, over a hundred years ago. But these configurations had never been tested in an actual microgravity situation. As was discovered when an unexpected "jump rope" or C-mode instability showed up in a simple rotating liquid zone experiment on Skylab, the presence of a neutral buoyant solution in a Plateau tank is a different boundary condition, which can often change the result of an experiment. Using the Fluid Physics module on SL-1 and D-1, the ability to model the behavior of such zones and to predict various instabilities was confirmed experimentally.

The surface tension of a liquid is also influenced by the presence of electric fields and can play an important role in miniature fluidics systems, which use electrocapillarity effects for pumping and manipulating fluids. Presently, the "leaky dielectric" theory developed by G.I. Taylor in 1966 is the only electrohydrodynamic theory applicable to this phenomenon and this theory had remained largely untested. It was shown on the Life and Microgravity Science (LMS) flight that liquid columns could be stabilized at lengths well beyond the Rayleigh limit by applying strong DC fields. However, contrary to the theoretical predictions, AC fields failed to stabilize the liquid columns at frequencies above the free charge relaxation times and a hysteresis effect was seen in the field required to stabilize the zone that depends on whether the field is increasing or decreasing. Now the investigator team is sorting out which aspects of Taylor's theory are correct and which parts need improvement.

#### Surface Tension Driven (Marangoni) Convection

In float zone crystal growth, there will be thermal and compositional variations along the axis of the zone. Since surface tension is a function of both temperature and composition, the unbalanced surface forces will cause flows along the surface that are often referred to as Marangoni flows after the Italian physicist. These return flows in the interior of the zone will tend to mix components, which may or may not be desirable, depending on the experiment. Above a certain Marangoni number, a dimensionless parameter that measures the ratio of heat conducted by the flow to the conducted heat, the flows become unsteady, a situation that must be avoided in a crystal growth experiment. Again the ability to model such flows and to predict the onset of unsteady flows was experimentally confirmed by the experiments on SL-1 and D-1.

Surface tension-driven flows along planar surface are important in many processes on Earth, such as crystal growth using the Czochralski process and pool burning (these flows may be seen in the wax pool of a burning candle as they bring new fuel up to the wick). In Earth's gravity, these flows are in competition with buoyancy-driven flows and it is difficult to sort out the two effects. Microgravity offers the possibility to study such flows without the influence of gravity and were the topic of a variety of experiments on a number of missions. One of the controversies in the ability to predict the onset of unsteady flows, was the role of surface deformation. This issue was settled on USML-2 when it was shown that a critical Marangoni number alone was not sufficient to predict the onset of instability and that an additional surface parameter must be specified.

### Bubble, Drop, and Particle Interactions

The bubble, drop, and particle unit (BDPU) developed by ESA and flown on D-2, IML-2, and LMS, proved to be an excellent workhorse facility for a variety of experiments ranging from the behavior of drops and bubble to pool boiling and even electrohydrodynamics. A drop or bubble in a thermal gradient will have unbalanced interfacial forces along its surface, which will tend to propel it in the direction of lower interfacial energy (usually from cold to hot). In 1959 Young, Goldstein, and Bloch developed a theory relating the motion of the drop to the Marangoni number. Since they did not have access to a microgravity environment, they tested their theory by balancing the surface tension forces against buoyancy forces on very small bubbles. One of the controversies in their theory was their assumption of a spherical drop and if the drop would be deformed under the combined effects of interfacial tension and Stokes drag. Motion of drops and bubbles in temperature gradients is important in many microgravity processes such as the removal of unwanted bubbles in solidification experiments and in phase separation in systems containing immiscible phases.

A variety of experiments were conducted to test the Young, Goldstein, and Bloch model. It was shown that indeed the drops remain spherical and that they do move in the direction of decreasing interfacial energy, but the model is only correct in the limit of zero Marangoni number (very small size) since the model neglects the heat transfer from the Marangoni flow. Also it was found that bubble motion can be retarded by the presence of certain components such as phenol groups in silicone oil which give rise to a "surface dilatational viscosity". Similar effects prevented bubble motion in experiments using tetracosane (molten paraffin).

Since the velocity of a drop or bubble depends directly on the radius, larger drops would be expected to overtake and engulf smaller drops. This effect is believed to be one of the mechanisms in the agglomeration of minority phase droplets during the solidification of monotectic alloys. However, it was found that a small drop leading a larger drop can slow the motion of the larger drop. When multiple drops are present, they do not always follow a straight path across the chamber, as single drops did. Instead, they followed a sinuous, helical path around their expected trajectory. Sometimes a larger trailing drop would actually move around and pass the leading drop. It is believed that such effects are

caused by thermal wakes left by the moving droplets that perturb the imposed thermal field.

### Pool Boiling

It is generally assumed that heat transport in boiling is largely the result of buoyancy driven convective flows. The bubbles that nucleate on the hot surface rise, carrying their latent heat with them. Similarly, the hot liquid near the surface, being less dense, will rise, causing overturning flows, which also carry heat away. The practice of cooling small electronic devices by immersing them in a pool of dielectric liquid with appropriate vapor pressure, such as a Freon, was considered by many not to be feasible in space because it was assumed that vapor would form around the device resulting in inefficient heat transfer. However, this assumption was shown to be incorrect on the LMS flight. Small heaters in the form of copper discs 1 to 3 mm in diameter, representing electronic components, were immersed in Freon 123. Surprisingly, the measured heat transfer coefficients were only slightly less than those measured in unit gravity. Thermocapillary jets were observed which appear to be an effective mode of heat transfer in microgravity and should also be effective in terrestrial boiling. These results may cause the theories of boiling in normal gravity to be revisited and it may be possible to design systems that take advantage of capillarity effects along with buoyancy to improve the efficiency of boilers on Earth.

### Drop Dynamics

The ability to suspend and manipulate liquid drops in microgravity provides an opportunity to test a number of classical theories describing the oscillations of liquid spheres. Confirmation of these theories using a tethered drop on Spacelab 1 and the drop physics module on Spacelab 3, USML-1, and USML-2 was crucial to the use of these theories to obtain various thermophysical properties of materials in their undercooled state on MSL-1R. The addition of various detergents to the drops on USML-2 illustrated how materials properties such as dynamic surface tension and shear as well as dilatational surface viscosities could be extracted from such measurements.

The drop physics module was also used to test the theory, developed by Chandrasekhar, describing the bifurcation of rotating drops that transitions from an oblate spheroid to a "dog bone" shape, which then fissions into two droplets. This theory has been applied to double star formation as well as to the liquid drop model describing nuclear fission. Earlier deviations from theory seen on Spacelab 3, were found to have been an effect of drop flattening from the acoustic pressure and that the theory was correct in the limit of spherical drops.

Other investigations carried out in the drop physics module elucidated the mechanisms by which core centering takes place in compound drops and liquid shells. Also non-linear effects from large amplitude oscillation, which eventually lead to chaotic behavior, were investigated. The former study has application to the fabrication of target shells for

inertially confined fusion experiments, while the latter applies to methods for increasing the evaporation and/or combustion of droplets.

### Critical Point Phenomena

A number of peculiar things happen in the vicinity of a second order or critical phase transition such as takes place at the terminal point of the coexistence region between a liquid and its vapor. Many of the thermodynamic properties change dramatically near the critical point, e.g., the velocity of sound as well as the thermal diffusivity goes to zero, while the heat capacity and compressibility becomes infinite. Other systems, such as a magnetic system near the Curie point (the temperature at which thermal motion becomes sufficient to destroy the magnetization) or the demixing of a homogeneous liquid into two immiscible liquids at the critical consolute temperature, exhibit similar behavior. The divergence of certain parameters near the critical point in each of these systems show the same exponential behavior, thus leading to the theory of universal behavior near a critical phase transition, regardless of the system. Ken Wilson was awarded the Nobel Prize in 1982 for applying group renormalization theory to determine the exponential behavior of these diverse systems near a critical point.

Since the compressibility diverges near the liquid-vapor critical point, even the smallest temperature difference can cause very strong convection, thus making it difficult to make measurements near the critical point on the ground which are needed to obtain accurate values of the critical exponent. Several early attempts to measure how the heat capacity diverges near the liquid-vapor critical point on D-1 were frustrated by the very long time it took to approach the critical point because the thermal diffusivity becomes vanishingly small. However, in the process, a new method for rapid heating by isentropic expansion, called the "piston effect", was discovered. Using this technique on D-2, heat capacity measurements were made only 0.9 mK away from the critical point, whereas the best ground based measurements could only be made 15-20 mK away from the critical point. The critical exponential term agreed with the theoretical value to within experimental error.

Another experiment circumvented the problems with the liquid-vapor critical point by choosing to measure the heat capacity associated with the transition of liquid helium to superfluid helium, the so-called lambda transition because the shape of the heat capacity curve resembles the Greek lambda. In microgravity, it was possible measure to within a few nK of the critical point, almost 100 times closer than in normal gravity. This experiment, flown on USMP-1 has provided the most accurate test of Wilson's theory.

A follow-on experiment on USMP-4 extended the heat capacity measurements near the lambda-point in which the He is confined to a spacing of 57 microns by carefully machined Si discs. The objective is to test scaling predictions for the transition to a lower dimension system. Normally, this transition takes place only when the dimension is on the order of Angstroms, but in semiconductors it can be as large as 0.1 micron, a length being approached by modern electronics. Since the correlation length diverges near a critical point, the distance over which the transition occurs can be greatly magnified.



Attempts are now being made to correlate the data from the flight experiment with theory and other measurements.

### Geophysical Fluid Flow Studies

The geophysical fluid flow cell, flown on SL-3 and again on USML-2, made use of microgravity to study the three-dimensional flow in a rotating hemispherical shell with an electric field providing the gravity-like central force. By varying the rotation rate and heating mode, this facility could simulate flows in planetary atmospheres as well as on the sun or in the Earth's mantle. A variety of interesting flow structures were observed as rotation rates and equator to pole heating was varied. The observed flows were used to check 3-dimensional computational models. Rotation with spherical heating produced banded patterns not seen before in numerical simulations and may provide an alternative view of the mechanisms responsible for the observed structure of the Jovian atmosphere.

In slow rotation experiments, climatic "states" in the form of two distinct convective patterns were found to exist with the same external conditions, differing only by the initial conditions. These patterns are persistent and are insensitive to small changes in the external conditions. Data was obtained on how these state break down under larger changes in operating conditions. The transition from anisotropic north-south "banana convection" to the more isotropic convection was studied. This information may lead to a scaling argument for classifying different planetary atmospheres.

Other experiments with latitudinal heating show evidence of baroclinic wave instabilities and successfully showed how spiral wave convection breaks down into turbulence.

### Combustion Experiments

There are two compelling reasons for the study of combustion in microgravity. One is the issue of fire safety in the design and operation procedures of orbiting laboratories; the other is take advantage of the weightless state to study certain combustion phenomena in more detail and to test various models in which convection has been ignored in order to be mathematically tractable.

As examples of the first category of experiments, smoldering combustion and wire insulation flammability studies were carried out using the glovebox on USML-1. Smoldering combustion can be extremely dangerous in a space station since it can remain virtually undetected for some time, but the increased temperature, due to the absence of convection to carry the heat away, can greatly increase the amount of toxic fumes generated. The wire flammability studies were carried out both without convection and with forced convection to simulate the behavior of possible electrical fire in space.

The geometry and behavior of a candle flame was studied using the glovebox on USML-1. Fiber supported droplet combustion experiments were carried out on USML-2. By tethering the droplets on a silicon fiber, they could be kept in the field of view of the video recorder so that the burning rate and other parameters could be recorded. The

objective is to test theories of droplet combustion and soot formation that are of importance to improving the efficiency of internal combustion engines, gas turbine engines as well as home and industrial oil burning heating systems. Microgravity allows to droplet size to be increased to as much as 5 mm so that the combustion process can be studied in detail. Once the theory is developed, its predictions can then be scaled back to the droplet sizes used in the actual combustion processes.

Soot formation in laminar flames was studied on the MSL-1R mission along with the Structure of Flame Balls at Low Lewis Numbers (SOFBALL) experiment. In the latter experiment, a container was filled with various combustible mixtures near their lean limit of combustion. A flame ball was created by an electrical spark. A stationary spherical flame front develops as fuel and oxygen diffuse into and heat and combustion products diffuse out of the flame ball. This is the simplest possible geometry in which to study the chemical reactions and the heat and mass transport of lean combustion processes. Over 50 years ago, Zeldovich found that the equations for steady heat and mass conservation had a solution corresponding to a stationary flame front, but he also showed that the solution was unstable. He did, however, consider the possibility that heat loss might be a stabilizing factor, which is apparently the case since some of the flame balls lasted the full 500 seconds until the experiment timed-out. It is expected that these experiments will provide new insight on combustion processes in the lean burning limit, which are important in improving the efficiency of engines and heating systems.

## Materials Science

Material science experiments carried out on Spacelab flights ranged from metals to glasses and ceramics with the bulk of the work focused on alloys and single crystal semiconductors. The alloy solidification experiments generally fall into three general categories: (1) experiments designed to understand how the microstructure evolves during solidification, (2) studies of interfacial effects that control the distribution of second phase particles, and (3) measurements of thermal physical properties.

### Evolution of Microstructure

The strength and other properties of an alloy depends on its microstructure which is characterized by the size, orientation, and composition of the grains that make up the solid. One of the main tasks of a materials scientist is to design solidification processes to produce the microstructure that will give the material the desired properties. With the present computational capability, it is possible to design a complex mold so that the heat and mass flow will produce the desired microstructure throughout the final casting. However, in order to do this, the basic laws governing the development of the microstructure must be known along with the thermophysical properties of the components. Establishing the physical basis for the various laws that describe the solidification process has, over the last half-century, transformed metallurgy from an industrial art based on empiricism to a more exact science. Because of the complicating effects of convection, many of the laws in use today are based on theories that assume no convective flows. We know that they don't apply exactly, but we use them anyway,

assuming they are basically correct, and then try to fix them up by adding the effects of convection. But most of these theories have never been tested in the absence of convection so various subtleties may have been overlooked. The ability to experiment in microgravity provides an opportunity to test some of these theories to make sure they are basically correct.

One example is the theory developed in 1968 by Jackson and Hunt that describes the microstructure of a eutectic alloy when it is solidified. When a eutectic alloy solidifies, it separates into two solid phases with different compositions that form parallel lamellas along the direction of solidification. Jackson and Hunt showed that the spacing between these lamella times the square of the solidification velocity is a constant that depends on the diffusion coefficient and other properties of the material involved. Since a eutectic solidifies congruently, i.e., a melt of uniform composition is transformed directly into a two-phase solid, there is little chance for convection to act, even in a gravity field and, indeed, the theory seemed to be correct. However, several early flight experiments found a larger spacing in their flight samples than in their ground control samples. This raised some interesting questions. Was there something wrong with the Jackson-Hunt model, or was something else going on in the microgravity environment that might account for the different spacing? One hypothesis was that thermal diffusion, sometimes referred to as the Soret effect, might shift the composition of the melt at the solidification interface away from the eutectic composition, which could account for the different spacing. Soret diffusion is very difficult to measure on the ground because of convective remixing. Another hypothesis is that microconvection occurs in the melt in the vicinity of the solidification interface that increases the effective diffusion rate that governs the separation of the two phases, resulting in a closer spacing in a gravity field.

A series of eutectic solidification experiments were carried out on Spacelab 1, D-1, and D-2. All but one experiment found increased lamella spacing in the flight samples. Although Soret diffusion may be the dominant effect in some of the systems, there were no apparent compositional shifts in the others, which argues for the microconvection theory. Apparently, the Jackson-Hunt model works in normal gravity because the diffusion coefficient and other properties are not known precisely enough to calculate the constant accurately. (See later discussion concerning the measurement of diffusion coefficients)

In most alloy systems, all components in a melt do not enter the solid lattice at the same rate, resulting in a buildup of the rejected component in the melt ahead of the growing solid. This compositional shift raises the local freezing temperature in the melt ahead of the solidification front. If a uniform composition is required in the final solid, as is usually required when growing single crystals of electronic materials, the material must be directionally solidified and a sufficient thermal gradient must be maintained ahead of the solidification front to assure that the temperature is everywhere above the local freezing point. Otherwise, the material becomes constitutionally undercooled, the plane solidification front breaks down and dendritic (fir tree-like) solidification occurs.

The transition from plane front solidification to dendritic solidification has been studied extensively. A simple criterion for the gradient required to stabilize the solidification front was developed in 1953 by Rutter and Chalmers, which is known as the constitutional supercooling or CS theory. Later, Mullins and Sekerka applied linear stability analysis and obtained a more refined theory for interfacial breakdown.

The French developed a sophisticated apparatus for studying the transition from plane front to cellular to dendritic solidification which measures the Seebeck voltage at the melt-solid interface to determine the amount of undercooling required to advance the solidification front and to detect the onset of interfacial breakdown. The official name of the apparatus is Materials for the Study of Interesting Phenomena of Solidification on Earth and in Orbit or MEPHISTO. One of the objectives of the flight on USML-1 was a definitive test of the Mullins-Sekerka theory in faceting as well as non-faceting eutectics. The apparatus was also used to investigate the effect of transient acceleration from a thruster firing on the solidification front.

In metallic systems, a fine grained structure is often preferred and the dendrite arms play an essential role in the evolution of the microstructure. Therefore, it is necessary to know how dendrites grow in order to design a given microstructure in a casting. Dendrites can form when solidification takes place in a medium where the surrounding temperature is lower than the local freezing temperature. This situation can occur either by constitutional undercooling in the case of alloy solidification, or by the fact that a certain amount of undercooling is required to nucleate the solid from either the melt or the vapor. A classic example of the latter is the formation of ice dendrites (snow flakes). Their intricate shapes have fascinated scientists and philosophers alike, and the study of their formation is the confluence of pure physics from the point of view of pattern formation and material science whose interest is in the evolution of microstructure in alloys.

A first attempt to model the growth of a dendrite was made by Ivantsov who approximated the trunk of a dendrite as a paraboloid of revolution and solved the heat flow equation that described the flow of the heat of solidification into the surrounding medium. He was able to obtain the growth rate  $V$  as a function of tip radius  $R$ . However, there seems to be no fundamental relationship that would select either a specific tip radius or growth rate in solidification processes. The question becomes, how does nature select a unique operating state? Experimental observations of pure systems suggest that  $VR^2$  is either a constant for a specific material, or a weakly varying function of the undercooling. A large body of terrestrial data has been taken on several systems, but convection effects, especially in the crucial region of low undercoolings where the growth rate is comparable to the convective flow velocities, have prevented an adequate test of the selection rules governing this process. This was the motivation behind a set of flight experiments carried out on USMP-2, 3, and 4.

Dendrites were grown in transparent organic metal analogs, succinonitrile which solidifies in a body centered cubic structure, and pivalic acid which solidifies in a face centered cubic structure. The use of transparent systems allows direct observation of the

growth process from which growth and other data may be extracted. The measured product of tip radius and growth velocity in microgravity falls much closer to the Ivantsov solution than the terrestrial data. The slight deviations may be attributed to the formation of side branches on the dendrites, possible wall effects from the growth chamber, and the fact the observed shape of the dendrite tip is a slightly different shape from the parabola assumed in the Ivantsov solution. Now that the heat transfer away from the growing dendrite is properly accounted for, the physics of shape selection can be approached with reliable data. A large number of highly detailed photographs of dendrites growing under carefully controlled and well documented conditions are now being used to study other aspects of dendrite growth such as the side arm growth rates and spacing.

In the meantime, investigators on D-1 took advantage of the larger dendrites obtained by solidifying an aluminum-copper alloy at low velocities in microgravity. By taking multiple cross sections, they were able to reconstruct, for the first time, an actual dendrite formed in an opaque alloy system of practical interest. The resulting reconstruction provided valuable information on the secondary and tertiary arm spacing and on the ripening of the dendrite arms. On the LMS mission grain refining inoculants were added to the system order to promote the nucleation of small grains ahead of the solidification front which grow dendritically in all directions, thus forming equiaxed dendrites. This allowed a test of a simple theory proposed by Hunt which relates the transition from columnar to equiaxed dendrites to the undercooling, the thermal gradient, and the number of nuclei, but ignores the effects of convection.

Ostwald ripening is responsible for grain growth and coarsening of the dispersed phase in dispersion hardened alloys. The original theory describing this effect was developed independently by Landau and Slyozov and by Wagner and is known as the LSW theory. But their theory is based on a mean field approximation which ignores the presence of other particles. Several theories have been proposed to correct for finite volume fractions of the dispersed phase but give quite different results. Microgravity experiments have provided data in molten systems without the complicating effects of convection, but are awaiting more accurate thermophysical data in order to properly evaluate the competing theories. It is interesting to note that Ostwald ripening also plays an important role in the development of ice grains which destabilize snowpacks and cause avalanches.

Other aspects of solidification were also studied in order to refine various models that are used to predict the final microstructure. These include liquid phase sintering and the study of order-disorder transitions.

### Interfacial Effects

When an advancing solidification interface encounters a second phase object such as a particle or bubble, the object can either be engulfed by the advancing solid or pushed ahead. The critical velocity, above which the particle will be engulfed, depends of the size of the object as well as the thermophysical properties of both the host solid and the second phase object. Being able to predict whether an object is engulfed or pushed is

important in the processing of dispersion hardened alloys, forming fiber-reinforced composites, and seemingly unrelated problems such the destruction caused by frost heave. Several theories that predict the critical velocity for simple systems have been tested and verified on five of Spacelab missions, but issues still exist when the situation is complicated by a dendritic rather than planar solidification front or when submicron particles agglomerate. One of the space experiments demonstrated that such agglomeration was not a gravity effect and that the van der Waals forces were not effectively shielded by the melt. These findings convinced one group of investigators that it was not practical to pursue attempts to form dispersion alloys by casting.

One of the first applications considered for microgravity was the formation of hypermonotectic alloys, alloy systems that have a region of liquid phase immiscibility. When solidifying such systems through the immiscible region in normal gravity, the denser liquid immediately settles out, resulting in complete phase separation. It was thought that this separation could be avoided by solidifying in microgravity, thus opening the door for hundreds of alloys that cannot be processed from the melt on Earth. Much to the surprise of the early space experimenters, these alloys also separated in microgravity, but for totally different reasons, many of which had not been considered previously. Such experiments have been carried out on seven Spacelab missions have produce a wealth of information concerning spinodal decomposition, nucleation and growth of liquid phases, critical wetting and spreading, and Marangoni-driven droplet motion. These experiments also helped develop a terrestrial strip casting technique in which bismuth droplets are suspended in a molten Al-Si alloy by balancing gravity forces against Marangoni forces. The resulting solid is used as a high performance, self lubricating bearings.

Another industrially inspired series of experiments explored the use of a thin oxide coating to support the shape of a molten sample in the absence of hydrostatic pressure. The motivation was to eliminate the thermal conductance of the mold during the recrystallization of superalloy gas turbine blades. So called single crystal blade are actually aligned column dendrites interspersed with the last-to-freeze interdendritic fluid. When the very small oxide particles were added for dispersion hardening, they tended to clump together. Without the mold, it was hoped to be able to apply a higher thermal gradient so that plane front solidification could be achieved at high enough speeds to engulf the oxide particles.

Actual turbine blades were coated with thin oxide layers and directionally solidified on D-2. The complex blade shape was maintained even through cross sectional area changes for cast blades without the oxide particles. However, the evolution of trapped gases in the blades prepared using power metallurgical techniques, where the oxide particles could be added, caused shape distortion and the particles still agglomerated because of other mechanisms. Even though the desired result was not achieved, this is an example of how an industry might use space to determine what the problem is not, which can also be a valuable piece of knowledge.

## Crystal Growth from the Melt

There are many difficulties in growing bulk single crystals of various electronic and photonic materials for use as windows and substrates for various devices. Since the properties depend on composition, it is necessary that the composition be as uniform as possible over the wafer the device is to be fabricated on. Since dislocations scatter and trap electrons, the number of dislocations and other electron traps must be as low as possible. Small angle grain boundaries and twins effect device performance and must also be eliminated.

Maintaining a uniform composition is particularly difficult in the growth of multi-component, alloy type crystals such as  $\text{Pb}_{1-x}\text{Sn}_x\text{Te}$  or  $\text{Hg}_{1-x}\text{Cd}_x\text{Te}$  which are used for infrared imaging devices. The bandgap of these systems varies with the composition  $x$ , which allows one to tune the detector to the desired bandwidth, but also requires that  $x$  be uniform over the detection area in order for every element to have the same spectral response. Since the different atoms go into the lattice at different rates, obtaining a uniform composition becomes a difficult task. Usually such systems are grown by directional solidification using the vertical Bridgman method to minimize convection.

If the rejected component is more dense than the bulk melt, as is the rejected Hg-rich component in the case of  $\text{Hg}_{1-x}\text{Cd}_x\text{Te}$ , the system is both thermally and solutally stable. The Hg-rich layer builds up in a diffusion layer in front of the growing crystal until an equilibrium is reached in which the Hg atoms enter the growing crystal at the same composition as they are in the bulk melt. After this transient region of varying composition, equilibrium growth should continue with uniform composition until the diffusion region encounters the end of the bulk melt. However, it is necessary to add heat to the melt through the sides of the growth ampoule and extract it through the growing crystal. This produces small radial thermal gradients in the melt causing the warmer fluid near the walls to rise while the cooler melt near the center falls. This circulation distorts the buildup of the diffusion layer at the growth interface resulting in radial segregation. It was hoped to be able to avoid these flows in microgravity and grow under diffusion controlled transport conditions.

Macrosegregation becomes a major problem in Bridgman growth of non-dilute or alloy-type systems when the rejected component is less dense than the bulk melt, as is the case in the Sn-rich rejected component of  $\text{Pb}_{1-x}\text{Sn}_x\text{Te}$ . When the diffusion layer builds up to a certain critical point, the lighter fluid will rise and remix with the bulk fluid. If the growth system is turned upside down to prevent this from happening, the system becomes thermally unstable. Thus it becomes impossible to stabilize such a system against overturning convective flows in the presence of gravity. Coriell performed a linear stability analysis on such systems that suggested that they might even be unstable in microgravity. Experiments using the NIZEMI centrifuge showed that Coriell's analysis was overly conservative since it did not include the stabilizing effects of the ampoule walls.

Being able to stabilize Bridgman-type growth systems presents a major challenge to the ability to control the residual acceleration of the spacecraft. When gravity is removed, the favorable density gradient no longer stabilizes the HgCdTe system and the slightest transverse acceleration will drive convective flows. The transport from these flows must be less than the diffusive transport if diffusion controlled is to be achieved. If the liquid diffusion coefficient is small, as it is for most of the systems of interest, the quasi-steady component of the transverse acceleration must be held to less than 0.1 micro-g. Since gravity gradient accelerations are typically on the order of 1.0 micro-g, the axis of the furnace must be aligned nearly along the residual acceleration vector if this condition is to be met.

An attempt was made to align the Crystal Growth Furnace (CGF) along the residual acceleration vector on the USML-1 mission. However, the force from the venting of the flash evaporator system on the Shuttle resulted in an unanticipated 0.5 micro-g transverse acceleration. The HgZnTe experiment (similar to HgCdTe) was accidentally terminated just as the growth was reaching steady state, but the effect of the transverse acceleration could clearly be seen in the composition of the sample. HgCdTe was flown on USMP-2 and PbSnTe was flown on USMP-3. However, in neither case was the Shuttle able to provide the necessary attitudes to satisfy the very demanding requirements needed to provide diffusion controlled growth. The major contributions from these experiments lies in the extensive research that went into their preparation in the form of measurements of pertinent thermophysical properties, analytical and computational modeling, and extensive ground based testing with and without strong magnetic fields. The measured redistribution of solute in the flight samples is being compared with the predicted values based on the accelerometer data in order to verify and refine the models that have provided a much deeper appreciation of the importance of convection in Bridgman crystal growth.

The unexpected 0.5 micro-g acceleration on USML-1 caused the melt in a CdZnTe sample to be nudged against one wall and become detached from the opposite wall. The side that solidified as a free surface had a much lower dislocation density than the side in wall contact and no evidence of twin formation was seen. This confirms an earlier observation on a semiconductor sample that had partially detached from a wall on one of the Skylab experiments. The experiment was repeated on USML-2 using a novel ampoule design that would minimize wall contact with the sample. Approximately half the sample grew with no wall contact, while the other half grew with partial wall contact. A second sample had a spring-plunger system that forced the sample to fill the ampoule, thereby assuring wall contact. Preliminary analysis showed that twin formation was virtually zero in the region grown without wall contact; whereas, the sample in the spring-loaded ampoule was highly strained at the exterior and heavily twinned. This experiment verified the contention that wall induced stresses are a major cause of the growth defects in crystals of this type grown on Earth.

The Europeans using their mirror furnaces on D-1 and D-2, focused primarily on various forms of travelling zone growth. Since only a small portion of the material is molten at any one time, steady state growth conditions with uniform composition can be achieved



if the melt is either diffusion controlled or if it is completely mixed, so long as the flows do not fluctuate with time. Therefore, the acceleration requirements for this class of experiments is not as stringent as for Bridgman growth. A number of compound semiconductor systems, including doped compounds such as GaAs, CdTe, InP, and GaSb, as well as the ternary PbSnTe were grown by the traveling solvent zone method (a method in which the zone contains an excess of one of the components to lower the melting point). For the most part, the space-grown crystals were free of growth striations and had lower dislocation densities than the ground control counterparts. In many cases, the melt had pulled away from the walls which may account for the fewer defects, thus reinforcing the findings from USML-1 and -2.

Considerable attention was also given to crystal growth using the floating zone technique in this series of missions. Striations were seen on doped-Si samples grown on the first Spacelab flight that closely resembling those seen on the ground control samples. This proved that the origin of these striations was due to unsteady Marangoni convection rather than buoyancy convection. However, it was found on a series of TEXUS suborbital flights and on D-1 that a thin (5 micron) coating of amorphous silica completely suppressed the Marangoni flows.

On the D-2 flight, GaAs crystals, as large as 20 mm in diameter, were grown. This is more than twice the diameter than can be grown by float zone in normal gravity. A special heater controlled an arsenic source to provide the necessary arsenic overpressure to maintain stoichiometry. As a result, no evidence was seen of either gallium or arsenic precipitates. The shape of the growth interface could be controlled by controlling the height of the molten zone. When the interface was nearly flat, the dislocation density dropped to  $5 \times 10^3 \text{ cm}^{-2}$ , two orders of magnitude less than typically found in Earth-grown GaAs. Rocking curve width, which measures the internal order of the crystal, was as low as 11.6 arc seconds, comparable to best quality crystals grown on Earth. Dopant striations were observed, which were attributed to unsteady Marangoni convection. A cobalt-samarium magnet was inserted near the end of several samples to help suppress the Marangoni convection, but the field was too weak to prevent unsteady Marangoni flows.

### Vapor Crystal Growth

For materials that lend themselves to physical or chemical vapor transport, growth from the vapor offers some attractive alternatives to growth from the melt. Growth can take place at temperatures considerably lower than the melting point, thus avoiding some of the higher temperature problems associated with melt growth. Gravity-driven convection will definitely influence the growth process, perhaps in ways that are not yet completely understood or appreciated. However, since diffusion is much more rapid in vapors than in melts, diffusion limited growth conditions can be obtained under far less stringent acceleration conditions than those required for melt growth and, since vapors must fill their containers, there are no free fluid surfaces that can drive Marangoni convection.

Experiments in which  $\text{Hg}_{1-x}\text{Cd}_x\text{Te}$  was grown on (100) CdTe substrates by closed tube chemical vapor transport (CVT) were carried out on USML-1 and USML-2 using  $\text{HgI}_2$  as the transport agent. Considerable improvements in the compositional uniformity and morphology of the films deposited in space were noted. Etch pit densities indicating dislocations were lower by one to two orders of magnitudes and electron mobilities were higher than the ground control by a factor of two (films were doped n-type from the incorporation of the iodine in the transport agent). These improvements were attributed to the sensitivity of the  $\text{Hg}_{1-x}\text{Cd}_x\text{Te-HgI}_2$  vapor transport system to minute fluid dynamic disturbances that are unavoidable in normal gravity.

Mercuric iodide ( $\text{HgI}_2$ ) forms a layered structure, similar to graphite, in which the A-B planes are bonded by van der Waals forces. Consequently, the crystalline structure is very weak, especially at the growth temperature, and it was thought that the performance of the material as a room temperature nuclear spectrometer might be limited by defects caused by self-deformation during the growth process. Mercuric iodide crystals were grown by physical vapor transport on Spacelab 3. It was possible to increase the growth rate on Spacelab 3 to more than twice the rate on the ground without spurious nucleation. The space-grown crystals exhibited sharp, well-formed facets indicating good internal order. This was confirmed by  $\gamma$ -ray rocking curves which showed a single peak and were approximately one third the width of the multi-peaked curves from the ground control crystals; however there was still evidence of lattice strain in the flight sample. Measurements just after the flight showed that both electron and hole mobility were significantly enhanced in the flight crystal, although, for reasons that are not clear, the values decreased after some time. The experiment was repeated on IML-1 with similar results. It is still not understood whether the improved quality of the flight crystals was due to the elimination of the weight of the crystal during its growth, or to the diffusion-controlled transport conditions that produced a more uniform growth environment.

### Solution Crystal Growth

A novel, cooled sting method for growing crystals from aqueous solutions was used to grow tri-glycine sulfate (TGS) on Spacelab 3 and IML-1. TGS is a long wavelength pyroelectric infrared detector material. Methods for the seed preparation were improved for the IML-1 experiment which resulted in an unprecedented success. Although, it was possible to grow only a small amount of material in the low-g time available, some very interesting results were obtained. In space it was possible to grow uniformly on the (010) face, whereas on Earth growth on this face is nonuniform and multifaceted. The detectivity ( $D^*$ ) and other parameters measured on the space grown crystals during the IML-1 show a definite improvement over the ground control crystals. For example, the dielectric loss tangent in the space grown crystal was 0.007, which is much lower than the 0.12-0.18 measured on the crystals grown by the cooled sting technique on the ground. The TGS crystal grown on the IML-1 mission was examined with high resolution monochromatic synchrotron X-radiation diffraction imaging using the National Synchrotron Light source at Brookhaven National Laboratory. The images indicate an extraordinary crystal quality as the local acceptance angle for diffraction from an uncut IML-1 flight crystal was found to be 1-2 arc seconds. The continuity between the seed

and the space grown materials is indistinct. The only inclusions visible in the high resolution X-ray topographs are due to the incorporation of polystyrene particles intentionally inserted in the growth solution to study the fluid motion in low-g.

Zeolites are a class of crystalline aluminosilicate materials that form the backbone of the chemical process industry worldwide. They are used primarily as adsorbents and catalysts. One of their most important roles is that of a "cracking" catalyst in the petroleum industry. New applications for zeolites include selective membranes, chemical sensors, polymer-zeolite composites, and molecular electronics. For these reasons, this is an intensive interest in obtaining a better understanding of how they nucleate and grow with the aim of being able to tailor their structure for specific applications.

Various forms of zeolite crystals, including zeolite-A, X, Beta, and Silicalite were grown on USML-1 and -2 with the aim of getting larger and more uniform crystals. In general, the crystals grown in space with nucleation control grew 10 to 25% larger in linear dimension than their ground controls. The zeolite-X crystals grown on USML-2 were 25 to 50% larger than their ground controls and twice as large as grown on USML-1. For the most part, the flight samples had higher Si/Al ratios than did their control samples and one of the A crystals exhibited the theoretical Si/Al ratio of 1.00, which not been seen before. Space-grown Beta crystals were free of line defects that are common in those grown on the ground. X-ray diffraction studies indicated slightly smaller unit cell volumes, which indicates fewer defects. A comparison of the catalytic activity of the space and ground-grown crystals has not yet been published in the open literature.

### Thermophysical Properties

One of the most interesting and potentially useful series of experiments had to do with the use of microgravity to measure thermophysical properties of materials in their molten and even supercooled state.

A diffusion experiment on Spacelab 1 not only measured diffusion coefficients that were substantially lower than the values measured on the ground, but the variation with temperature suggested a  $T^2$  dependence rather than the Arrhenius-like dependence seen in most solids. This result prompted a series of liquid-liquid diffusion experiments on D-1, D-2, SL-J, and LMS. Generally the diffusion coefficients were found to be 30-50% lower when measured in microgravity and, with one exception, seemed to follow a power law with an exponent close to 2. These findings imply that: 1. all of the liquid diffusion measurements made on Earth are probably contaminated to some degree by convection effects; and 2. the vacancy diffusion model that has been applied successfully to solid diffusion does not apply to liquids. At the present, there is no viable model for the liquid state that predicts a  $T^2$  dependence of the diffusion coefficient. Therefore, these results could provide new insight into the theory of the liquid state.

An impressive number of thermophysical constants can be measured without physical contact from an electromagnetically positioned molten sphere. Surface tension and viscosity can be obtained by exciting vibrational modes and measuring their frequency

and damping rate. The heat capacity, thermal conductivity, and total hemisphere emissivity were measured using A.C. calorimetry in which the heating field is modulated at frequencies ranging from 0.05 Hz to 0.2 Hz. The heat capacity is related to a correlation function of modulation frequency, the internal (heat up) relaxation time, and the external (heat loss) relaxation time. Also, thermal expansion and volume change on melting can be determined by direct observation of the suspended drop. A change in electrical resistance with temperature in the sample changes the inductance of the heating coil. Thus by measuring the voltage, current, and phase of the heating current, resistivity can be inferred. Although it is possible to levitate conductive samples in unit gravity, the heating effect from the levitating field makes it difficult to undercool the material. Also the shapes become highly distorted and spherical samples are required to extract much of the thermophysical data.

There is considerable interest in the properties of the undercooled state of the glass-forming metals. In order to estimate the cooling rate required to form a metallic glass, it is necessary to know the difference in the Gibbs free energy between the solid and the liquid state as well as the viscosity and the interfacial energy. The Gibbs free energy is the enthalpy of the liquid less the product of the entropy and temperature. The enthalpy of the liquid can be obtained by integrating over the heat capacity of the undercooled liquid.

The TEMPUS electromagnetic levitator was flown on IML-2, but many of the samples became contaminated before the experiment began in space. The problem was corrected and the instrument was reflown on MSL-1R, which produced some very interesting results. The heat capacities of the liquid state were found to be considerably higher than the Dulong-Petit limit for solids. The viscosities appeared to follow an Arrhenius law, although the scatter in the data was such that a power law dependence could not be ruled out (see previous discussion on diffusion constants). Surface tensions tended to decline linearly with temperature. The electrical resistivity of  $\text{Co}_{80}\text{Pd}_{20}$  alloy was found to increase linearly with temperature in both the solid and liquid state, but with a higher value and slightly steeper slope in the case of the liquid. Solid  $\text{Co}_{80}\text{Pd}_{20}$  is a good ferromagnet with a Curie temperature of 1250 K. The measured inductance in both solid and in undercooled melt exhibited a dramatic change, beginning when the material was cooled below 1360 K and showing a sharp increase at 1250 K. This increase was interpreted as magnetic ordering. There had been speculation as to whether a ferromagnet could exist in the liquid state. There appears to be no fundamental reason to believe that it could not; it's just that the Curie temperature of every known magnetic material happens to lie below its melting point. This is the first evidence suggesting that ferromagnetism does indeed exist in the liquid state.

In a related experiment, samples of Ag-Ge and Fe-Ni were able to be deeply undercooled in a  $\text{B}_2\text{O}_3$  lined crucible. The  $\text{B}_2\text{O}_3$  acts as a flux, and keeps the metal sample away from the crucible walls, thus denying the metal melt low energy nucleation sites. Two of the FeNi samples actually hypercooled (hypercooling occurs when the enthalpy of the melt becomes lower than the latent heat of fusion, so that the sample cannot return to its

melting temperature during recalescence). Therefore, this technique offers an alternative way of making heat capacity measurements in the undercooled state.

### **Glass Formation**

Microgravity offers a number of potential advantages for the formation of unique glasses, but so far only a few experiments have been conducted to explore these advantages. Lithia-silica and  $\text{Na}_2\text{O}-\text{B}_2\text{O}_3-\text{SiO}_2$  glasses formed in a crucible on D-2 showed greater homogeneity than the ground control based on variations in refraction analysis and microprobe analysis. The difference was ascribed to the fact that nuclei that formed at the wall were not transported to the remainder of the melt in microgravity.

The Single Axis Acoustic Levitator, originally developed as a suborbital facility, was flown on D-1. A sample of low viscosity gallia-calcia-silica was successfully melted and solidified without contact. A glass was formed at a much slower cooling rate (2 to 3 times slower) in space than is possible in a crucible, which reflects the absence of low energy nucleating sites on the levitated sample.

## **Biotechnology**

The Biotechnology investigation carried out on Spacelab missions include protein crystal growth, electrophoresis, electrofusion, and various cell culturing and plant growth experiments with commercial implications. The vast majority of the experiments were devoted to the growth of protein crystals. Experiments dealing with living organisms, including the remainder of the cell culturing and plant growth experiments, including those performed in the Biorack, will be covered under Life Sciences.

### **Biomolecular Crystal Growth**

Some of the most exciting results from the Spacelab missions have been in the field of biotechnology. Spacelab can legitimately claim to be the genesis for the expanded interest in the growth of protein and other biomolecular crystals, which are necessary for understanding biological function at the molecular level. X-ray diffraction is the only method for obtaining the three-dimensional structure of complex biomolecules that determines their function and crystals of a certain size and perfection are necessary for this analysis. Structure-based drug design is an emerging technology that shows great promise. For example, neuraminidase is an enzyme required by all strains of influenza virus to replicate. Three pharmaceutical houses are using the structure of this enzyme to develop inhibitors which have the potential of treating all strains of influenza.

When Walter Littke reported that he was able to grow larger crystals of lysozyme and beta-galactosidase on Spacelab-1, Charlie Bugg, then the Associate Director of the Comprehensive Cancer Center at the University of Alabama in Birmingham (UAB),

immediately recognized the implications of this result and organized molecular biologists, who were having difficulty growing large enough crystals of their materials of interest, to try to exploit the perceived advantage of microgravity for protein crystal growth. After several tries with simple hand-held experiments to work out the details of the growth technique, they were able to clearly demonstrate, not only that it was possible to grow larger crystals in microgravity, but some of the crystals had better internal order than the best crystals ever grown on Earth by the most qualified researchers.

These results provoked theorists as well as experimentalists, who previously had concentrated on the growth of inorganic small molecule crystals, to ask why should these macromolecular crystals grow better in microgravity? Suddenly, the task of growing biomolecular crystals, that had been simply an obstacle for molecular biologists to overcome, became a science unto itself, receiving funding from NASA as well as from NSF and NIH. These studies have transformed what had been largely a shotgun-approach to growing biomolecular crystals to a more exact approach by providing solubility data, modeling the transport, assessing the effects of impurities, and examining the dynamics of the growth interface in order to establish the conditions under which growth instabilities might occur. The insights provided by these studies have suggested ways for improving crystal growth as well as explaining why some growth systems may not grow as well in space as they do on Earth.

Larry Delucas, the Payload Specialist on USML-1, demonstrated the advantage of a trained crystallographer onboard to set up and monitor the crystal growth experiments, intervening when necessary, to optimize the growth process, which is different in space than on the ground. For example, he found that mixing of the protein and the precipitating agent in many of the automated experiments that had been set up on the ground was not adequate, especially when a viscous precipitating agent such as polyethylene glycol was required. By mechanically mixing the precipitating agent on orbit, he was able to grow diffraction quality crystals of several proteins that previously had not been successfully grown in space.

In the meantime, the success of the group headed by Bugg and later by Delucas, inspired other leaders in the field to develop new concepts for growth facilities to be used in space. Alex McPherson and Dan Carter in the US organized teams interested in using the growth facilities they had developed, while ESA developed their advanced protein crystal growth facility which can accommodate a variety of growth methods and provide diagnostics of the growth process.

It should be recognized that many crystals are generally required to obtain sufficient data to solve a structure. However, often one crystal that can provide even a small increase in resolution, when merged with data from other crystals, may be key to either solving the structure for the first time, or for refining a structure so that the active site may be mapped more accurately. Thus far, US sponsored Spacelab experiments have been able to improve the resolution of 5 different proteins by as much as 0.5 to 1.0 Å, 3 proteins to between 0.3 and 0.5 Å, and another 25 proteins by up to 0.3 Å.

After the structure of a target molecule has been determined to good accuracy, there is still a major task ahead before an effective drug can be designed and selected for clinical trials. Each candidate drug must be complexed with the target molecule and more crystals are required of the complex in order to determine how well the drug fits the active site. After the more promising candidates are selected, there is still the long and torturous procedure required to take it through FDA approval cycle and bring it to market. Thus it can easily be a number of years before the benefits of many of these space experiments will be seen by the general public.

Some of the more promising drugs under development, in which space played a significant role, are summarized below:

Pharmaceutical companies had been searching for way to control the release of human insulin so that diabetics could take fewer injections and have a more constant supply. One promising binding agent turned out to be toxic to humans. Space grown crystals provided the clue as to what was going was going on and led to a solution of the problem.

Factor D is a protein that often stimulates the immune system to overreact from the trauma following open heart surgery. A particularly large crystal of this protein grown on USML-1, when merged with other data, provided the structural information. Drugs to block this protein are in Phase II clinical trials and may be available by 2001.

Space grown crystals of Glyceraldehyde 3-phosphate dehydrogenase (GAPDH), an essential enzyme in the parasite that is responsible for Chagas' disease, were instrumental in refining this protein. Drugs based on the structure of this molecule are in pre-clinical trials.

NAD-synthetase is a target for a wide spectrum antibiotic under development that pre-clinical trails have shown to be effective against anthrax, pseudomonas, and flesh eating bacteria. Space grown crystals played a role in obtaining its structure. A crystal grown on STS-95 improved the resolution from 1.6 Å to 0.9Å. These data should prove useful to help improve knowledge of the active site if it becomes necessary to adjust the design of the drug that is presently being tested.

The Center for Macromolecular Crystallography, a NASA-created Commercial Space Center, now employs more than 100 scientists and engineers working on crystal growth, structure determination, and the next generation of flight experiments. They collaborate with 37 universities and have 21 industry partners that contribute over \$2 million per year in direct funding. There are now 4 spin-off companies (BioCryst Pharmaceuticals, Inc., Ibbex Pharmaceuticals, Inc. and Diversified Scientific, Inc., in Birmingham and New Horizons Pharmaceuticals in Huntsville) that have been created as a result of the NASA-sponsored work in this area.

## Electrophoresis

Electrophoresis, and its related electrokinetic separation processes such as isoelectrofocussing, are widely used for separation of proteins on an analytical scale. The protein molecules take on a particular surface charge (zeta potential) in a buffer solution. When an electric field is applied, the molecules will be move under the influence of the applied field. Usually, the proteins are caused to migrate through a gel. The combination of the attraction by the applied field and the drag through the pores of the gel give each protein a specific mobility so that they will become separated spatially as the process is continued. Because this process is limited to microgram quantities, it is used primarily as an analytical tool.

Attempts to scale electrophoresis to a preparative scale by replacing the gel with a continuous flowing sheet of sample plus buffer solution have enjoyed only limited success on the ground, primarily because buoyancy driven convection places severe restrictions on the sample concentration and the thickness of the flowing buffer sheet. These factors limit the throughput of continuous flow electrophoresis (CFE); consequently, it has largely lost popularity to other methods, such as column chromatography, as a preparative separation method. There are certain potential advantages to CHE, however. It is a universal method, as opposed to column chromatography, where the columns have to be designed to separate specific proteins. Also, it can be applied to cell separation without having to tag the cells as is required by various cell sorting techniques.

There are reasons to believe that continuous flow electrophoresis could be carried out more efficiently in space from two points of view. First, the thickness of the flow chamber could be scaled up without encountering the convective distortions that limit the scale on terrestrial machines. Second, it should be possible to increase the sample stream concentration without sedimentation problems. Combining these two factors could theoretically increase the throughput by several hundred over Earth-based machines.

However, increasing the concentration of the sample stream can create additional problems if the conductivity and dielectric constant are different from the buffer fluid. Such differences in electrical properties distort the sample stream and can even lead to flow instabilities. One of the motivations for the series of electrophoresis experiments carried out in the French "Recherche Applique sur la Methodes de Separation Electrophorese Spatiale" or RAMSES on IML-2 was to examine these electrohydrodynamic effects without the complicating distortions caused by buoyancy. Other experiments used the Japanese Free Flow Electrophoresis Unit (FFEU) to evaluate its ability to carry out various separations. Bubbles in the buffer curtain and various technical problems allowed only limited success in this set of experiments.

## Commercial Biotechnology

Two other NASA-sponsored Centers for Space Commercialization conducted biotechnology experiments on USML-1 and -2 in addition to a series of Spacehab flights.



The Wisconsin Center for Space Automation and Robotics (WCSAR), has developed ASTROCULTURE™, a state-of-the-art plant growth chamber for space as well as terrestrial research in which the many variable involved in plant growth can be controlled. One of their goals is to provide the means for on-orbit food production for extended missions. This activity has produced a number of commercially useful spin-offs including a novel system for delivering water and nutrients to plants, an air humidification/dehumidification system that does not need a gas or liquid separator, and an efficient LED lighting system for plant growth that is also finding medical applications. Their work on utilizing microgravity to improve the process of transgenic plant alterations could also have significant societal and economic benefits by producing food crops that mature faster.

The BioServe CSC is carrying out an extensive research program to catalog how various organisms respond to the microgravity environment with the goal of exploiting those characteristics they find useful for commercial purposes. Many of their findings, such as the accelerated growth of certain organisms, enhanced production of cell products, enhanced enzymatic activity, etc. in microgravity are surprising and are not understood from simple fluid modeling of gravity effects in living organisms. Their academic collaborators at the University of Colorado, Boulder, and Kansas State University in Manhattan, Kansas have published a very impressive number of papers on their findings. One of the more promising areas of their research has to do with the effects of microgravity on plant production of lignin. Attempts are being made to understand how this comes about and perhaps use this information to genetically engineer plants on Earth to control the production of lignin. There is significant interest in both the paper industries, who wants less lignin in their pulp wood, as well as the timber industry, who wants more.

## **Life Sciences**

Life sciences experiments were flown on 17 of the 36 Spacelab missions between 1981 and 1998. More 375 separate experiments were designed, developed, and conducted by more than 138 principal investigators and 536 co-investigators. Over a thousand publications and reports were published and results from more recent Spacelab missions, including Neurolab, are just beginning to appear in journals.

Life sciences experiments fall into three major discipline areas which are: 1) Advanced Human Support Technology, 2) Biomedical Research and Countermeasures, and 3) Gravitational Biology and Ecology.

### **Gravitational Biology and Ecology**

#### **Cell and Molecular Biology**

Cell and molecular biology investigations were conducted on eight of the 17 Spacelab missions which included Life Sciences experiments. They were flown under the Life Sciences discipline category "Gravitational Biology and Ecology". The experiment specific categories included cell growth and metabolism, organelles and structures, immunology, hematology, bacteria and viruses, yeast, circadian rhythm, and protoplasmic streaming.

In the interpretation of all cell biology experiments flown in space, it is important to understand that differences in growth, metabolism and function can reflect differences in hardware used as well as the particular characteristics of launch, payload location on the Shuttle, and other mission and experiment specific parameters including temperature changes during an experiment, length of the mission, starting and stopping of the 1g in-flight reference centrifuge during sampling, and storage of samples. Significant differences in response to spaceflight are also cell type and culture dependent. Not all cell types respond in the same way to conditions of spaceflight. A number of cell lines flown on the various Spacelab missions showed virtually no response to microgravity. Examples include Murine Friend Leukemia Virus transformed cells and Hamster kidney cells (ATCC CCI 15) grown on Cytodex 3 microcarrier beads. Hybridoma cells flown on Spacelab D-1 showed only a slight change in metabolite production, whereas Hybridoma cells of a sub-clone of the cell line 7E3-N showed a decrease in the production of monoclonal antibodies, which seems to argue against the use of microgravity for the production of monoclonal antibodies. Monkey kidney derived cultured cells (JTC-12) flown on SL-J showed evidence of cytoskeletal/membrane interface perturbation induced by spaceflight.

A landmark experiment by Cogoli et al. on the Spacelab 1 mission was the first to show a dramatic, quantitative response to spaceflight at the single cell level. Normal peripheral human T lymphocytes were growth stimulated in flight by addition of Con-A. In microgravity, activation of the cells was 90% less than that of the ground controls. This

result was confirmed on D-1. Additional experiments on IML-2 indicated that the first step in T-cell recognition of antigen appears to be significantly compromised in microgravity. In the experiments flown on SLS-1, Cogoli mixed microcarrier beads with the cells as a way to increase cell contact interactions. The results were surprising. Although lymphocytes do not normally attach to substrata, the cells attached to the microcarriers and activation in microgravity, in response to Con-A, was now double that of ground controls. The cells without microcarrier beads again failed to respond to Con-A thus confirming the SL-1 and D-1 results.

Other experiments on IML-2 demonstrated that cell-cell contacts, necessary for T cell activation, do occur in microgravity. Addition of microcarrier beads promotes activation two-fold higher than ground controls yet, without beads, lymphocyte activation in microgravity is almost totally abolished. Reasons for this are not clear. The impact to crew health on long term missions because of impaired cell mediated immunity is not known and remains a significant biomedical area to be investigated.

Previous studies on U.S. biosatellites and Soviet Salyut missions showed an increase in bacterial growth rate. The experiments conducted on Spacelab D-1, D-2, IML-1, and USML-1 confirmed that the growth rate in bacteria as well as some other organisms is increased. In addition, antibiotic sensitivity is reduced and genetic transfer between bacterial cells is different in microgravity compared to ground controls. It was found that the increased growth rate, not the permeability of the cells, is the primary reason for reduced response of bacterial populations to antibiotics during spaceflight.

Yeast cells (*Saccharomyces cerevisiae*) were flown in a miniaturized bioreactor on IML-2. No remarkable differences were found in cell cycle, proliferation, cell volume, ethanol production or glucose consumption and no morphological anomalies were found.

*Paramecium tetraurelia* had been shown in previous flight experiments to increase growth rate and cell volume significantly and decrease cell dry weight and protein content. A comparison of data from microgravity and the 1g in-flight shielded centrifuge on D-1 demonstrated that effects on *Paramecium* growth and volume in space are due to the effect of microgravity and not to cosmic radiation.

The microscope equipped NIZEMI centrifuge on IML-2 was used to determine the threshold for gravitaxis on two species of ciliates, *Paramecium* and *Loxodes*, and on the slime mold *Physarum polycephalum*. *Physarum* does not have a specialized structure for gravity perception, yet it showed a very low threshold (0.1 g) for gravitaxis.

Two different strains of the unicellular green algae, *Chlamydomonas reinhardtii*, were used on D-1 to evaluate circadian rhythm. No differences were found between flight and the ground control, thus this organism appears to have an endogenous biological clock. Cell proliferation and survival rates in microgravity were higher and no mutations were found in flown samples.

#### Developmental Biology

Developmental biology experiments were flown on eight Spacelab missions. A total of 24 experiments were conducted and seven different species were studied including insects, brine shrimp, jellyfish, amphibians (frogs and newts), fish mouse, and quail.

Experiments to determine the effects of spaceflight on the development of *Drosophila melanogaster* were carried out on Spacelab D-1, IML-1 and IML-2. Oocyte production was significantly increased in microgravity compared to the 1g in-flight centrifuge and ground controls. Embryos continuously exposed to microgravity were larger than controls. Larvae showed thoracic and/or head abnormalities in the microgravity samples. The lifespan of adult males continuously exposed to microgravity was only 75% of their normal lifespan, while the lifespan of females was unaffected.

The development of graviceptors of the ephyrae of *Aurelia aurita* (Jellyfish) was studied on IML-2 and on SLS-1. There was no difference in morphology between space and ground developed ephyrae but abnormalities were found in their pulsing behavior. This suggests an abnormal development of graviceptors or the neuromuscular system or a defect in the integration of impulses between the systems.

Sea urchin larvae (*Sphaerechinus granularis*) were flown on IML-2 to determine whether mineralization and formation of skeletal structure occur properly and if larvae with skeletons already developed on the ground would lose mineral in microgravity. Significant results were that larvae developed skeleton in flight and no pronounced loss of mineral from already formed skeletons occurred. However, the skeletons that were formed showed some unusual architecture indicating that the process of association and positioning of the cells which determine the size and shape of the skeleton are particularly sensitive to environmental perturbations. Evaluation of calcium and magnesium did not show significant differences between flight and ground samples.

Five of the Spacelab missions, D-1, D-2, IML-1, IML-2 and SL-J, included investigations into the role of gravity and weightlessness on developing amphibian eggs. These experiments used eggs of *Xenopus laevis* (African three-clawed frog) to determine if fertilization occurs in microgravity and if embryo development is initiated. *Xenopus* eggs, fertilized and developed in microgravity, form normal axis and neural plates and the tadpoles develop normally. The inner ear of juvenile developing newts flown on IML-2, showed significantly larger saccular otoliths and some differences in assembly of components of the otoconia.

Alterations in gravity environment induced somewhat pronounced long-lasting behavioral reactions followed by long-term adaptation to the gravity changes. Changes in brain biochemistry were found in fish and tadpoles subjected to hypergravity (3g) and electron microscopy data showed that after exposure to microgravity energy metabolism was reduced in neurons in the gravity integration center of the brainstem. There were also changes in the gravity-sensitive epithelial cells in the inner ear of fish larvae. The tadpoles swam in narrow somersaults, in circles or floated motionless in random positions. Some of the fishes swam in large circles or darted around randomly or floated

motionless. After return to earth, fishes re-adapted and swam normally after about 16 hours but the tadpoles continued to swim in circles, loops or in screw-like patterns for at least six days.

Avian development was evaluated on chicken eggs fertilized before launch on SL-J and quail eggs on a series of Spacelab Mir Missions. For chick embryos, all tissues including cartilage and bone formed in 7 and 10 day old chick embryos during spaceflight. After flight, these chicks continued to develop and hatched normally.

## Plant Biology

Plant biology experiments were flown on 11 of the 17 Life Sciences Spacelab missions. More than 30 individual experiments, most with multiple objectives evaluating multiple plant types, were conducted addressing the general areas of plant growth and development, gravity sensing and response, metabolism, lignification and support hardware development.

The results on plant growth and development from experiments performed on a number of plant types (oat, mung bean, anis callus cultures, rapeseed protoplasts, wild carrot, arabidopsis and its mutants and hemerocallis or daylily and a fungal sp.) showed that responses are generally plant type and species specific. In general, seed germination and plant growth progressed well in microgravity. Root orientation is strongly dependent on gravity but amyloplasts resting on the endoplasmic reticulum or cytoskeletal elements does not account totally for all gravity-sensing mechanisms in plants and mechanisms are still unclear. The thresholds (minimum g-force required to elicit a response) were surprising low. Use of the NIZEMI centrifuge-microscope allowed visualization of the bending responses of seedling roots. This provided extremely significant information on the influence of gravity related to developing plants on Earth as well as the effects of microgravity.

Leguminous plants formed nodules in presence of Rhizobium bacteria. This showed that gravity is not necessary for normal co-development of nitrogen-fixing bacteria and leguminous plants and is important information for future cultivation of legumes on space stations, long-duration missions or Lunar outposts.

Lignification was significantly reduced in microgravity. Without the requirement to grow strong stems to hold plants upright as in 1g, the plants adapted to microgravity by reducing lignin synthesis.

A commercially developed and available plant growth facility, Astroculture™, allowed cultivation of potatoes (1.5 cm diameter in approximately 16 days) in microgravity. Technology developed as a part of this facility is being used for ground-based purposes ranging from treatment of cancer patients to horticulture. Still in the area of plant growth facilities development, the Greenhouse experiment conducted in the Russian/Slovakian-developed plant growth facility called the "Svet" was launched on SL-Mir. Probably one

of the most complex plant experiments ever attempted in space, the facility grew plants for 90 days on Mir to allow seed-to-seed growth.

## Radiation Biology

Experiments to evaluate radiation levels and effects on living systems and to obtain information on levels of radiation within the spacecraft and Spacelab were flown on five of the 17 Spacelab missions that included Life Sciences payloads. Sixteen radiation experiments were flown, ten of which evaluated effects on life forms including insects, bacteria, mammalian cells, nematodes, yeast, and plants. Five experiments provided information on the levels of radiation in different locations on the Shuttle and in some of the experiment specific hardware including Biorack, the access tunnel, pallet, and the Shuttle middeck. One experiment reported dosimetric information on crew. Radiation has been an topic of biomedical concern since the beginning of human spaceflight and must be taken into consideration, either as to effect on individual experiments or experiment specific hardware shielding) when any biological experiments are conducted in space.

The primary type of radiation evaluated, HZE, is cosmic radiation produced by heavy, high energy and charge particles (ions) released by interactions of primary galactic radiation with the Earth's atmosphere. This densely ionizing component of cosmic radiation is most damaging to cells and tissues. Hits by HZE cause damage to cells from the nuclear disintegration stars produced by protons and neutrons in the irradiated tissue. Another type of radiation that should be considered comes from ionizing components of the radiation field. These include photons, electrons, muons, pions and protons.

Radiation surveys on SL-1 and IML-1 concluded that the radiation exposure on astronauts during the mission was higher than the mean annual public exposure but well below the limits defined for spaceflight. Heavy ion flux in different positions within Biorack varied between 0.5/cm and 0.2/cm. Comparison of results from IML-1 and IML-2 showed a higher heavy ion flux variation for the different locations in IML-2 (a factor of more than six compared to a factor of two in IM-1). Thus the conclusion was that the only way to obtain confident information about radiation intensity and type is to measure radiation on each mission in the vicinity of the experiment of interest. Assumptions made that the Biorack facility components shield biological experiments may not be totally valid. A similar measurement of the same general areas of Biorack on D-1 provided additional information that experimental conditions for biological experiments in space must consider that dosimetric data may not be sufficient for proper assessment of test data. At the cellular level, hits are not evenly distributed and thus averaging of radiation doses in the general area may not provide accurate information for the experiment.

On SL-1 and D-2, experiments were conducted to evaluate the effects on prokaryotes of vacuum and solar ultraviolet radiation, separately and in combination. On D-2, 308 biological samples were exposed to solar UV, vacuum, or a combination of both. As shown on SL-1, reduced survival of *B. subtilis* was more evident in samples exposed to

both vacuum and UV-radiation. Survival was affected by the repair capacity of the strains investigated and injury of the spore DNA in the form of DNA strand breaks was assumed to be the mechanism of damage.

Eggs of the stick insect, *Carausius morosus*, have different sensitivities when exposed to cosmic radiation at different developmental stages. Experiments flown on Spacelab D-1 and IML-1 show that effects of HZE particles (heavy ions of high charge and energy) from cosmic radiation combined with microgravity are synergistic. Yeast cells irradiated with X rays before launch were capable of repairing some of the damage, however; the repair rate was reduced in microgravity samples. However, an experiment on IML-2 found no significant differences in the rejoining kinetics of radiation induced double-strand breaks of DNA in *Escherichia coli* PQ37 or in a human primary fibroblast line. In human skin fibroblasts the rejoining kinetics were almost identical in microgravity, in the ground control, and in the 1g in-flight centrifuge control. Similarly, the *E. coli* strain PQ37 also repaired its DNA under all gravity conditions. These results were corroborated by another experiment on IML-2 using *Bacillus subtilis*. The spores were irradiated on the ground before flight and allowed to germinate in static microgravity, in the 1g in-flight centrifuge, as well as in ground controls. Results again proved that DNA repair can be initiated and function normally in microgravity.

### **Biomedical Research and Countermeasures - Animal Physiology**

Animal physiology studies flew on six of the Spacelab missions. Animal physiology experiment specific areas included bone, muscle, cardiovascular, neurophysiology, renal physiology and endocrinology, immunology, metabolism and nutrition, and chronobiology. There were more than 100 individual animal physiology experiments flown which included species of mouse, fish, and avian; however, the rat was the most studied species.

#### **Bone**

Skeletal loss in the long bones, primarily weight-bearing bones, is well documented yet mechanisms are not clear. Earlier experiments on Cosmos unmanned orbiting spacecraft showed that production and mineralization of bone matrix was retarded, contained fewer collagen fibers, and collagen was less mature in flown versus ground controls. The effect of microgravity on cartilage development and bone formation can result in marked skeletal changes including decrease in bone volume and altered biochemical properties. Loss of bone mass remains one of the most important biomedical concerns to long-duration human habitation of microgravity environments.

Thirteen experiments to investigate effect of microgravity on bone and cartilage formation, mineralization, endocrinology, and metabolism were flown on five of the Spacelab mission. An experiment on SL-3 showed that even during a short spaceflight, less matrix is formed and there is less mineralization in rat bones. As a follow up to investigate production of collagen by bone primary mouse bone cells in culture was flown on IML-1. This experiment addressed chondrogenesis in skeletal development.

Endochondrial ossification involves collagen synthesis as well as other factors. Conclusions were that, although chondrocytes could function, proliferation of rough endoplasmic reticulum and production of matrix did not occur in flown cells. An experiment on SLS-1 showed that bone regenerative potentials decreased, thus stimulating the process of osteoporosis.

Metabolic studies on SLS-1 evaluated bones, blood plasma, and endocrine factors that participate in bone metabolism regulation. Limb bones and lumbar vertebrae were evaluated. Results showed decrease secondary spongiosa and increased bone resorption surface in proximal metaphyses of tibiae. These are signs of developing osteoporosis. These changes correlated with biochemical data showing decreased alkaline phosphatase activity and increased activity of tartrate-resistant acid phosphatase (a bone resorption enzyme). There were decreases in bone calcium, phosphorus, sodium and chloride and depressed function of thyroid C-cells producing calcitonin which is necessary for normal mineralization of bone matrix. Mineral metabolism changes confirmed previous findings that calcium is higher and phosphorus is lower in blood of flown animals. Somatotrophic activity was depressed in the pituitary leading to decreased synthesis and secretion of growth hormone.

Thirteen experiments investigating muscle physiology in rats were flown on three Spacelab missions. The soleus, a primary weight-bearing muscle sometimes referred to as the antigravity muscle, was the subject of several investigations. As was predicted, the soleus showed the most dramatic changes in response to microgravity. Flexor muscles such as the tibialis anterior, and extensor muscles (extensor digitorum longus) were not significantly affected by gravitational unloading in microgravity.

Spaceflight induced significant fiber shrinkage or atrophy and increased expression of fast muscle characteristics (fast myosin) in slow fibers. In addition muscle damage, resulting from muscle atrophy in microgravity, that occurred postflight included thrombosis of microcirculation, interstitial and cellular edema, muscle fiber fragmentation, sarcomere disruptions, activation of phagocytic cells, elevated ubiquitin conjugation suggesting protein breakdown. Accelerated aging-like involution of neuromuscular junctions was found in caged rats, thus was not just a characteristic of spaceflight. The abductor longus muscle appeared more susceptible to damage probably due to resumption of activity after flight.

### Cardiovascular Physiology And Hematology

Human adaptation to microgravity results in loss of red blood cell (RBC) mass, reduction in plasma volume and decrease in total blood volume. Spaceflight-induced anemia is the subject of a number of investigations to discover the potential mechanisms. Use of rats as a model to investigate space adaptation responses on the Spacelab missions proved an excellent means to investigate space anemia.

Experiments on SL-3 demonstrated a significant increase in hematocrits (ratio of packed cells to whole blood volume), RBC counts, hemoglobins and neutrophils. (The increased



cell counts could be due to artificially increased concentrations because the plasma volume was reduced in spaceflight as a result of fluids shifts and loss in microgravity. Also found was a significant reduction in the percentage of lymphocytes, which confirmed earlier reports that lymphocytes are affected by spaceflight. Bone marrow, spleen and erythropoietin (EPO), the hormone that stimulates RBC precursors in the bone marrow to development into mature RBCs, showed no significant differences between flown and ground animals. Bone marrow cells of flown rats could be induced by EPO to produce erythroid colonies, thus the changes in RBC numbers was apparently not due to faulty cell response to EPO stimulation.

In humans, characteristic adaptation to upper body fluid shifts in space include increased heart rate, blood pressure and total peripheral vascular resistance, and decreased venous pressure. Upon return to Earth, re-adaptation causes severe increase in heart rate and low blood pressure. Results of the study with heart tissue removed from rats after flight on SLS-2 showed that contractile strength of heart muscle was decreased.

### Endocrinology

Experiments to determine the effects of microgravity on hormone and regulatory peptide synthesis and release have shown that spaceflight has significant effects on animal physiology. Most (12) of the animal physiology experiments were flown on the Spacelab-3 mission. One flew on SLS-1 and five endocrinology-related experiments were flown on SLS-2.

Fluid shifts to the upper body during spaceflight is related to changes in fluid regulating hormones. Atrial natriuretic factor (ANF) is one of the hormones that regulate fluids shifts. ANF is secreted in response to increased pressure in the cardiac atria from increased shift of fluids to the upper body. ANF activates membrane-bound guanylyl cyclase coupled receptors (GC-A receptors). A second type of guanylyl cyclase coupled receptor is an apparent target for a natriuretic peptide in the brain. A third receptor appears to be coupled to adenylyl cyclase. Other hormones including vasopressin, catecholamines, in addition to ANF regulate response to fluids shifts and rennin influences blood pressure. Atriopeptin (AP-3) is released when right atrial stretch receptors are stimulated (possibly by fluid shifts in microgravity). The atriopeptins cause natriuresis and diuresis by direct action on the kidney as well as inhibition of aldosterone and vasopressin secretion and dilation of large vessels resulting in further central pooling of blood.

### Metabolism And Nutrition

Nine experiments were flown on three Spacelab missions, SL-3, SLS-1 and SLS-2, to investigate the digestive and metabolic changes that occur during and after spaceflight. Previous experiments with animals have shown that spaceflight significantly affects metabolism.

The Spacelab mission experiments advanced understanding of the qualitative and quantitative changes in lipid metabolism, the interactions between function of endogenous intestinal microflora and digestive function, and digestive enzyme activity and function during and after spaceflight. Metabolic breakdown of nutrients, medications, and many hormones occurs in the liver and numerous hepatic enzymes regulate catabolic function. Adaptation to spaceflight includes biochemical changes in the liver to accommodate energy requirements, including glycolysis and lipid peroxidation. A 20-fold higher glycogen content was seen in flown rats post-flight compared to ground controls on SLS-3. In addition, glucose levels and enzymes of the citric acid cycle were decreased and glycolysis and ATP synthesis was increased.

Experiments on SLS-1 showed that spaceflight did not significantly affect the antioxidant protection component in liver and other tissues but after return to 1g, readaptation caused changes in antioxidant protection.

Endemic intestinal microflora provide enzymes that interact synergistically with the host to facilitate digestion in the small intestine. A very important finding was that lipid metabolism was greatly altered by spaceflight. Lipase activity was significantly decreased and short chain fatty acid concentration was significantly increased, indicating a different energy providing metabolism in microgravity. An experiment on SLS-2 suggested that changes in basic metabolism in erythrocytes and lymphocytes were due to structure and function of their membranes because lipid and phospholipid composition of the membranes was changed. This can be extremely significant to the understanding of mechanisms responsible for blunted lymphocyte response to antigen stimulation during spaceflight.

### Immunology

Five experiments were flown on three Spacelab missions, SL-3, SLS-1 and SLS-2, to investigate immune response of rats exposed to spaceflight. Results of previous experiments have demonstrated that immune system alterations occur in animals and humans as a result of spaceflight. These are detected immediately after flight and after time, appear to normalize to pre-flight function. The immune changes predominantly are manifested as decreases in proliferation and function of T lymphocytes reflected as changes in cytotoxic activity of natural killer cells and production of cytokines.

An experiment on SL-3 sought to determine if weightlessness alters interferon-gamma (IFN-gamma) production by spleen cells of flown rats. It appears that the reduction in T lymphocyte number or function or stress per se could be responsible for the observed lack of IFN-gamma production by the spleen cells of flown rats.

Other experiments flown on SLS-1 and SLS-2 The cells from rats dissected immediately after landing did not grow in contrast to increased growth of cells from rats dissected 14 days post-flight. Activity of spleen natural killer cells was reduced during and after flight and returned to normal after 14 days at 1g. No significant changes in bone marrow natural killer cell activity were found between flight and controls. Production of

interlukin 1 and 2 and tumor necrosis factors alpha and beta in spleen cell cultures of flown rats was reduced. At landing, INF-alpha and gamma were diminished.

In summary, cell-mediated immunity in rats was significantly suppressed during spaceflight.

### **Neurophysiology**

Fifteen experiments were flown on four Spacelab missions, SL-3, SLS-1, SL-J, and SLS-2, to investigate the effects of spaceflight on the brain and nervous system and general neurophysiology of animals.

Physiological systems are generally regulated by the nervous system and many of these systems have been shown to be affected by spaceflight. Temperature regulation, fluid volume and water intake, calcium metabolism and neuromuscular control of movement are all altered in the microgravity environment. Viewed as adaptations to microgravity, these functions are mediated by changes in brain neurotransmitter interactions.

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### **Biomedical Research and Countermeasures - Human Physiology**

The Spacelab missions contributed significantly to the understanding of human physiological adaptation to the space environment and re-adaptation to 1g post-flight. Experiments addressed the areas of bone, muscle, cardiovascular and pulmonary physiology, hematology, kidney function, endocrinology, immunology, neurophysiology, and circadian rhythm. A total of more than 50 human physiology experiments were conducted on seven of the Spacelab missions.

#### **Bone**

Bone is a dynamic tissue that is continuously undergoing remodeling by the interactions of osteoblasts to build, and osteoclasts to destroy bony tissue. Not only does bone function in support, protection, and movement and as a reservoir for the stem cells that differentiate into cells of the immune system and blood, but bone is also a storage tissue for fat and minerals. Calcium is involved in a large number of normal cellular processes and maintenance of nervous system homeostasis and when the level of calcium is low in the bloodstream, it is recruited from bone. Deposit and release of bone calcium and minerals goes on almost continuously.

Rapid loss of bone mass occurs under microgravity conditions because of the exit of calcium and other minerals. Loss of bone is one of the most important health-related concerns that could affect the well being of humans to limit future exploration of space.

Due to the lack of impact stress, which is normally provided by walking in Earth gravity, bone mass and the levels of hormones that regulate calcium in the body, decrease significantly causing calcium resorption from bone into the bloodstream. The disruption of calcium metabolism and balance, while adaptive in microgravity, causes serious imbalances in the body. Bone resorption appears to begin immediately upon reaching microgravity and the increased calcium levels in the bloodstream cause higher excretion of calcium in urine and decreased absorption by the intestines. Countermeasures are not simple since increased calcium intake in microgravity could cause still more urinary excretion of calcium and increase risk of kidney stones.

Human bone physiology experiments were conducted on six of the Spacelab missions. The experiments addressed bone metabolism, calcium flux and mineral loss, and the hormones related to maintenance of bone. Objectives were to advance understanding and provide information on causes of bone loss and possible countermeasures to prevent this loss during spaceflight.

Osteocalcin, a non-collagenous protein in bone is synthesized by osteoblasts and its plasma level can be used as a marker for osteoblast activity and bone metabolism. High levels of osteocalcin in the plasma usually indicate fast growing bone. An experiment on Spacelab D-1 designed to evaluate osteocalcin in plasma from blood drawn before launch, in-flight and after landing did not show significant differences in osteocalcin levels that could be attributed to flight. On SLS-1 it was found that serum ionized calcium increased dramatically on flight day 2 to levels 40% above control in all crewmembers tested. This level is considered to be severe hypercalcemia. At day eight, serum ionized calcium levels remained high, 35% above normal, indicating that clinically significant hypercalcemia was maintained throughout the flight. Parathyroid hormone (PTH), released when blood levels of ionized calcium decline, decreased to about 50% of control throughout the flight. (PTH causes calcium release from bone matrix by stimulating osteoclast activity and bone resorption). The finding that PTH was decreased, biologically validated the increase in serum ionized calcium and negated the possibility the PTH caused the hypercalcemia.

## Muscle

Humans were the subjects for a number of Spacelab mission investigations on muscle physiology and adaptation to microgravity. Experiments were flown on five of the missions.

The muscular system and neural control components of the neuromuscular system are significantly affected by spaceflight. Just after launch, very rapid adaptation in motor control to hypergravity and then to microgravity must occur. The degradation in skeletal muscle function after time in space may be in part, an outcome of altered motor functions or how humans move in microgravity. In addition, impaired musculoskeletal function has been noted in astronauts after spaceflight. Both muscle atrophy and neuromuscular control and contractile force of individual muscle fibers may contribute to decrease in muscle strength. Data from animals flown on Spacelab-3 and Cosmos 1887 indicated

that skeletal muscle atrophy predominantly affects the slow-twitch fibers in muscles of animals. In humans, the responses may be different. Experiments on Shuttle missions have shown a greater atrophy of fast-twitch fibers.

### Cardiovascular Function

Cardiovascular adaptation in microgravity occurs rapidly and is characterized by shift of as much as 2000 ml of fluid toward the upper body. The experiments on human subjects to evaluate cardiovascular response in microgravity were generally involved with fluids shifts, heart function and orthostatic intolerance upon return to 1g. Investigations were conducted on seven Spacelab missions and more than 26 experiments with multiple sub-investigations were achieved.

Astronauts generally experience decreased performance, facial edema, over swelling of the veins, and stiffness in movement early in the mission. While cardiovascular adaptation in microgravity is rapid and effective, the orthostatic intolerance that occurs after spaceflight is associated with significant dysfunction and clinically apparent orthostatic intolerance. Characteristically, some astronauts feel faint and exhibit varying degrees of disability in standing. On D-2, it was found that maximal cardiac pump performance was maintained in space. In the upright position after flight stroke volume was reduced by about 25% and heart rate increased 35% with a parallel increase in peripheral resistance. This confirmed SLS-1 data which showed standing heart rate after flight increased from 82 beats per minute preflight to 98 postflight and the stroke volume were decreased from 52 ml preflight to 42 ml postflight.

An experiment on D-2 to evaluate fluid shifts within superficial tissues of the upper and lower parts of the body found that tissue thickness decreased about 16% around the tibia and increased by 7% in the forehead. It is estimated that about 410 ml of fluid leaves lower limbs and about ml accumulates in the superficial tissues of the head. Swelling of the head decreases within three to five days in space but does not disappear until after landing.

The intraocular pressure preflight measured about 10 mm Hg whereas, immediately after entering microgravity, this pressure increased by about 100%. After four to five days on orbit, pressure declined to preflight values. Twenty minutes after landing, intraocular pressure decreased about 30% less than preflight values.

Experiments on SL-Mir showed that long duration spaceflight effects are similar to short-term exposure. Most autonomic cardiovascular adaptations occur within the first days of spaceflight. On Mir, these changes persisted for at least four months in flight. Conclusions from the SL-Mir experiments were that long-duration spaceflight did not cause higher incidence of orthostatic problems compared to shorter duration Shuttle flights. This should be confirmed with a larger test subject pool in the future flight experiences. Heart rate and blood pressure during re-entry showed a lower than expected, small increase over values seen during normal preflight and intravehicular activities.

## Hematology

Hematology experiments were flown on SLS-1 and SLS-2 and SL-Mir. A consistent finding after spaceflight has been a significant reduction on red blood cell (RBC) mass. Experiments on SL-Mir again showed a rapid decrease in total blood volume (12%) within 24 hours. This decrease in plasma volume caused an apparent increase in hematocrit compared to preflight values. Erythropoietin levels in the serum were reduced also. The release of newly produced RBCs, which is under the control of erythropoietin, was terminated immediately after entering microgravity. It was concluded that down-regulation of RBC production during spaceflight is due to ineffective erythropoiesis resulting from decreased erythropoietin release into the serum. Additional studies on Mir 18 over longer time will be very useful. The adaptation process to microgravity with regard to RBC mass and survival represents a state of anemia which can be used to gain understanding of the mechanisms of erythropoiesis during spaceflight.

## Immunology

Changes in immune response have been consistently found in astronauts and cosmonauts yet the mechanisms are not clearly understood and impact to health and productivity of flying long-duration missions has not been determined. The immune system involves both cell-mediated response of T-lymphocytes and the production of antibodies (humoral or blood-borne) by B-cells. B-cells are specialized white blood cells that release antibodies into the bloodstream when stimulated by infectious organisms. The T-cells to rid the body of cells infected with bacteria, viruses, fungi and parasites. Maintenance of immunity in the body occurs by a very complex cascade of molecular and cellular events involving differentiation of cells and secretion of cytokines (cellular messenger molecules) and production of immunoglobulins. One experiment on SL-Mir was designed to investigate whether antibodies are produced in response to antigen introduced by vaccination and to determine the time course of the response. This experiment is long-term beginning with STS-71 in 1995 and continuing on Shuttle-Mir missions for several years. The second experiment series was designed to determine the phenotypic alterations in circulating immune cell subpopulations during spaceflight compared to populations observed immediately after flight and to assess functional changes in the peripheral immune cells. The roles of specific cytokines including interleukin 1, interleukin 1 receptor antagonist, and interleukins 2, 6, and 10, tumor necrosis factor alpha, granulocyte/macrophage colony stimulating factor and immunoregulatory factors such as prostaglandin E2 are being evaluated to assess spaceflight-induced immune suppression.

Additional information may be accessed as it becomes available on internet websites.

## Pulmonary Function

The human lung is very sensitive to gravity therefore on Earth there are large differences in gas flow, blood flow and gas exchange between upper and lower portions of the lung. On earth, pulmonary blood flow (perfusion) is greater near the bottom of the lung and

becomes smaller toward the top. Gas flow (ventilation) is distributed throughout though there are still large differences. Generally it is believed that these differences are primarily due to the pull of gravity. Comprehensive studies of pulmonary function on SLS-1 and SLS-2 and D-2 missions showed however, that much of the imbalance in lung ventilation and perfusion is maintained in microgravity.

### Kidney Function

Early in the flights, astronauts loose 2 to 4 Kg of body mass, mostly due to extracellular fluid volume loss. The objective of experiments flown on SLS-1 and SLS-2 was to gain further understanding of adaptive changes that alter fluid, electrolyte, renal and circulatory status of humans in microgravity. Preliminary results indicate that glomerular filtration rate was elevated in flight especially on flight day 8. Plasma volume was 22% lower than preflight and extracellular fluid volume was 15% below preflight value and was still low at day 8. Fluid intake and urine volume decreased sharply and mean intake remained at least 20% below preflight values throughout the mission.

Data from SL-M showed that extracellular fluid was reduced from 19.5 to 15.6 liters. These values are similar to those from a 14 day Shuttle mission. Conclusions are that changes in fluid volume that occur early in a flight, remain throughout long-term missions. Levels of two hormones important for fluid and electrolyte homeostasis (antidiuretic hormone and atrial natriuretic peptide) were reduced after 110 days of spaceflight.

Factors predisposing humans to increased risk of renal stones include excretion and negative calcium balance as a result of bone mineral loss, decreased urinary output after the first few days in microgravity, urinary pH changes, magnesium and citrate concentrations and increased urinary phosphate. These changes all can increase urinary supersaturation of stone-forming salts. Seventy percent of the renal stones in humans on Earth are composed of calcium oxalate and the remaining 39% are uric acid, struvite and cystine stones. Studies from Shuttle missions of 4 to 14 days on a total of 150 astronauts showed that immediately after flight, urine of most crewmembers is saturated with stone-forming salts placing them at risk of developing calcium oxalate and uric acid stones. There was also a difference in stone-forming salt concentrations between the short-and long-duration missions. Studies on SL-M and continuing long-term on Mir are designed to further investigate the effect of long-term habitation in microgravity on risk of development of kidney stones.

### Neurophysiology

Space motion sickness affects approximately 50% to 75% of Shuttle crewmembers in gradations of severity and presents a problem early in short-duration missions especially when the workload is heavy. It is important to understand the threshold for perception of vestibular inputs in order to improve methods for prevention, prediction and treatment of space motion sickness. Neurophysiology experiments were flown on seven Spacelab missions and more than 18 individual experiments have been conducted. Results from the

Spacelab Neurolab Mission are not currently available and will be appearing in the literature and internet websites increasingly over the next months and years.

Some of the findings are generalized in the following:

After flight all subjects showed an increase in postural instability and a strong tendency to sway when the visual field rotated.

- No consistent vestibulo-ocular reflex changes were noted on orbit.
- Pointing accuracy was very poor. The bias was toward pointing low. Performance was always better with eyes closed only while pointing. In this case results were similar to ground. Recovery to preflight accuracy returned by 7 days postflight. This shows that primary adaptation in microgravity is loss of the external spatial map and complete recovery requires several days after flight.
- Muscle fatigue showed that isometric muscle strength was reduced by 10% to 50% postflight in ankle plantarflexion and unchanged in dorsiflexion. The fatigability did not return to baseline by day 7 postflight.
- The threshold for perception of direction of linear acceleration was not significantly changed.
- Susceptibility to space motion sickness (SMS) was not predictable based on ground tests. After day 3, SMS dropped and remained low thereafter. Postural bias was negatively correlated with discomfort. (Crewmembers became sick without regard to position of the body in the spacecraft).
- Sensations of trunk tilt and respective concomitant reflexes are missing in microgravity when the head is tilted with respect to the trunk.

The effect of autogenic feedback (motion tolerance, autonomic control) was investigated as a countermeasure for space motion sickness. It was found to be effective in some but not all crewmembers. Individual autonomic response to spaceflight was different from ground simulation tests.

### **Advanced Human Support Technology - Human Factors**

Human factors include all of the factors across the disciplines that impinge on the health, performance, safety, and well-being of humans in orbiting spacecraft, planetary bases and space stations.

#### **Environmental Contaminants**

Microbial evaluation of the crew, air, surfaces and water on the Mir Station is critical to understanding the ecology of microbial organisms that inhabit crew living areas. Based on findings over the past 25 years it is evident that microbial ecology on spacecraft undergo quantitative and qualitative changes. Investigations on microbial biota from **SL-Mir** provide information on incidence and mechanisms of microbial transmission between crewmembers and work station/crew transmissions. Isolations of organisms from air, water and surfaces were shown to be within the International Space Station acceptability limits.



The environment of spacecraft contain chemical contaminants that can be potential threats to crew health and safety especially on long-duration missions, These airborne pollutants must be identified and controlled and air must be scrubbed and rendered compliant with safe levels. Evaluations of air quality are a significant part of the human factors considerations.

On Mir, approximately 50% of the potable water supplied to crewmembers is produced by direct recycling of water from humidity condensate. The other primary source is from potable water delivered by re-supply spacecraft from the ground or from fuel cell water that is transferred from the Shuttle. Experiments to assess the reliability of the water supply system are done to support future water requirements for future International Space Station needs based on information from Mir. Water samples collected on Mir 18 mission and on the STS-771 Shuttle mission were analyzed and considered to be of general potable water quality although it exceeded water quality standards for total organic carbon (TOC). Ground supplied water was considered of general potable water quality although it exceeded standards for TOC , turbidity and chloroform. These investigations are ongoing and modifications are considered for future flights.

#### Microgravity Environment Effects On Cognitive Performance Of Humans

Space travelers are subjected to a number of stresses during spaceflight. These include physical isolation, confinement, lack of privacy, fatigue and changing work/rest cycles. Studies on Earth have shown that changing work/rest cycles can degrade cognitive performance and productivity. A battery of cognitive test were administered on IML-2 and on LMS to determine the effect of microgravity on cognitive skills critical to the success of operational tasks in space. The tests include a number of cognitive, mood, fatigue, memory and performance tests. No general conclusions can be drawn at this time, given the limited number of subjects.







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